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Technical Report

AIR REVITALIZATION UNIT FOR SEALED SURVIVAL SHELTERS

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AIR REVITALIZATION UNIT FOR SEALED SURVIVAL SHELTERS

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by

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ABSTRACT

An air revitalization unit for use with sealed survival shelters without an external power supply was developed. The unit is capable of supplying oxygen to and removing carbon dioxide and odors from a 100-man personnel shelter for a 24-hour period. The system utilizes (1) a dry chemical absorbent (Baralyme) for carbon dioxide removal, (2) pressure cylinders for the oxygen supply, (3) an activated charcoal filter to remove odors, and (4) a battery-powered fan for air circulation. A prototype unit was designed, fabricated, and tested. Following tests of individual components, a 24-hour continuous test of the unit was completed. In general, the test results for the chemical, mechanical, and structural aspects of the air revitalization unit were affirmative. A similar assessment cannot be made for the human element inherently involved with the operation of the unit.

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INTRODUCTION

In the event of a nuclear attack both military operations and civilian survival coordination would be directed from protective structures. During this emergency, personnel occupancy in the underground installation might extend to 2 weeks. Normally, outside air would be used for ventilation. However, a supply of outside air is not assured. Circumstances could arise where the mechanical ventilation system of the shelter would be rendered inoperable because of power supply or equipment failure, or because of mass fires or firestorms, thereby requiring that the underground installation be isolated from the surface.

In 1965 the Naval Facilities Engineering Command (NAVFAC) requested that the Naval Civil Engineering Laboratory (NCEL) investigate the problem of supplying oxygen to and removing carbon dioxide and odors from a sealed protective shelter without an external power supply and then develop an air revitalization unit to cope with the problem. The project was performed in three parts—concept study, design, and test and evaluation.

BACKGROUND

Concept Study

A study was made to develop concepts for a system which would mitigate by chemical environmental control the undesirable effects of the vitiated shelter atmosphere.[1] Chemicals and equipment currently in use or being contemplated for use in submarines and space capsules were investigated. The study included regenerative systems and nonregenerative systems which were purported to be capable of manual operation.

Nonregenerative systems contain a store of chemicals which are continuously being depleted when the system is in operation. Once the chemicals have been used, air revitalization ceases. Nonregenerative systems are better suited for installations where an interruption of the power supply may more likely occur. Although they normally require electrical power for operation, they can be designed for manual or very low power operation.

A regenerative system consists of equipment which operates continuously and indefinitely as long as it is supplied with power. It usually has a high power demand, so therefore it cannot be manually operated. Therefore, it is better suited for installations with reliable emergency power. Several regenerative systems have been developed for use aboard nuclear submarines, but the practical usefulness of most of them has not been established for emergency shelter use.

The five concepts which were developed are described briefly in Table 1. Of these, two nongenerative systems, concepts 1 and 5, appeared to be the most attractive.

Concept 1. Concept 1 would use the enzyme of carbonic anhydrase along with conventional materials to control and absorb carbon dioxide. Since this system was not within the state-of-the-art for emergency shelter applications, a contract was let to the Electric Boat Division of General Dynamics, Inc. to evaluate the potential of the system. The investigation was divided into two phases—Phase I, process study, and Phase II, concept study. All work under the contract was completed in October 1967 and the results were reported by the contractor in References 2 and 3.

The Phase I effort included a feasibility study of three chemical solution absorbents, an analysis of the relative merits of each, and the solution recommended to be used in developing the Phase II, concept study. The three solutions originally selected for evaluation in detail were potassium hydroxide, sodium hydroxide, and potassium carbonate–bicarbonate–carbonic anhydrase mixture. The solutions were tested using a packed-column section with concurrent flow of scrubbed habitat air and recycled absorbent solution. Operating variables, such as solution concentrations, percent conversion, airflow rate, and solution flow rate were evaluated. Of the three, the potassium hydroxide solution was generally superior and was recommended for the Phase II, concept study.

The Phase II effort was concerned with the study of two concepts, each of which used a 5-foot packed-column section with concurrent flow of liquid absorbent and recycled air from the habitat. It was concluded that the most promising concept would be a manually controlled system based on an initial batch process which would proceed to a continuous feed and bleed process after the desired carbonate concentration was reached. It was further concluded that a solid carbon dioxide absorbent system would be generally superior to a chemical solution absorbent system.

Table 1. Concept Summary

No.	System Concept	Type	Oxygen Supply	Carbon Dioxide Removal	Size (ft)	Power (hp)	Comments
1	Enzyme	nonregenerative	pressure cylinders or chlorate candles	carbonate and bicarbonate salts plus the enzyme of carbonic anhydrase	4-1/2 x 4-1/2 x 6	100 people - 0.03	Recommended for further study
2	Tower	nonregenerative	superoxide	superoxide	unknown	none	Superoxide hazard
3	Impregnated liner	nonregenerative	superoxide	superoxide	unknown	none	Superoxide hazard
4	Battery, regenerative	nonregenerative for CO_2 removal, regenerative and nonregenerative for O_2 supply	split-cell batteries with cylinders for stand-by	lithium hydroxide or Baralyme	5 x 7 x 5	100 people - 37.0 800 people - 295.0	Requires electrical power
5	Hydroxide	nonregenerative	pressure cylinders	lithium hydroxide or Baralyme	5 x 7 x 5	100 people - 0.03 400 people - 0.10 850 people - 0.25	Recommended for design and fabrication

Concept 5. Concept 5 would use conventional materials proven reliable by existing submarine and space craft life support systems. This concept would use the hydroxides of earth metal salts for carbon dioxide removal and high-pressure oxygen cylinders for the oxygen supply. Included in the system would be an activated charcoal filter to remove odors and a fan for air circulation. Because of the high probability of success and because concept 1 did not warrant further attention, the concept 5 system was selected for development.

Design

The design which evolved from Reference 4 was used to prepare specifications for a prototype unit in which the most suitable environmental control techniques were integrated with the total requirement of the shelter. The design was developed in three phases—the evaluation parameters and design criteria were established, the chemical and mechanical components were selected, and then the components were arranged.

Three evaluation parameters—operational, functional, and economical—were established. Operational parameters dealt with the human element and included safety, simplicity, and power availability. Functional parameters dealt with the chemical and mechanical aspects of the unit and included reliability, efficiency, power requirements, and operating temperature range. Economic parameters included not only cost but also volume and weight requirements.

Since this unit was being designed for general use (that is, not for some specified facility), the design criteria, although somewhat arbitrary, were based primarily on NAVFAC specifications from Reference 5. It must be stressed that the application of this unit is limited to a shelter atmosphere that, because the structure has been sealed, is not subject to external contaminants, such as chemical and biological warfare agents. The basic criteria are summarized as follows:

Shelter capacity: 100 sedentary adults

Sealed occupancy period: 24 hours

Air circulation rate: 3 cfm per person

Unit airflow resistance: 0.25 inch of H_2O at 300 cfm

Unit power requirements: 0.03 hp

Operating temperature range: $35^{\circ}F$ to $90^{\circ}F$

In the prototype unit, odors would be removed by a filter using 30 pounds of activated charcoal. Oxygen would be supplied by pressure cylinders storing 2,500 scf of oxygen. Carbon dioxide would be removed by 960 pounds of Baralyme, a dry chemical absorbent. The Baralyme would be in a parallel bed arrangement made up of 24 trays. Baralyme was selected as the most promising absorbent—safest to use, lowest airflow resistance, least expensive—based on a literature search followed by an experimental evaluation. Air would be circulated by a battery-powered fan. The batteries would remain on trickle charge while the unit is inoperative.

Test and Evaluation

The final step in the development of the prototype unit is reported here. In addition, the most significant factors influencing prototype design are discussed briefly.

DESIGN CONSIDERATIONS

Operational Parameters

Manual Power. Studies to determine sustained manual power output have been conducted under Office of Civil Defense contracts in connection with the development of emergency shelter ventilation equipment. The selection of a bicycle-type drive was common to all of the investigations. The manual power input was determined to be a limiting factor. In Reference 6, it was concluded that an average man could produce 0.1 hp for several hours. This conclusion was challenged in Reference 7, where average men were tested and were found to be capable of producing 0.1 hp for 7 to 10 minutes before excessive tiring. A more extensive test program was reported in Reference 8, where 0.1 hp was produced for a 3-hour shift which was divided into 22-1/2/7-1/2-minute work/rest cycles. The participating group was comprised mostly of college students.

Unfortunately, no test has been conducted at elevated effective temperatures, no test has been conducted in a vitiated atmosphere, and no test has been conducted with an average male cross sectional group. Furthermore, the role of a NAVFAC shelter, operational or otherwise, has not been so defined that a reasonable estimate of the physical capacity of shelter occupants can be made at the present time. In short, it was concluded that a potential health hazard from overexertion existed and that the power supply was a most significant parameter.

When the developmental phase of this task was initiated, the general lack of confidence in a manual power supply combined with no definite information on which to base an estimate of the power requirements for the system resulted in a division of effort between minimizing the power requirement and circumventing the need for manual power. In a sense, both were successful. Experimental work with the carbon dioxide absorbent, which was discussed in detail in Reference 4, indicated that a total system pressure drop of 0.25 inch of water was feasible. This, combined with a 300-cfm airflow rate and 60% fan efficiency, would require a 0.02-hp input. In the meantime, the use of a specialized storage battery power supply was found suitable for survival shelter applications.

Simplicity of System. The development of the PVK (Package Ventilation Kit) for the Office of Civil Defense provided invaluable human factors input for the design of the air revitalization unit.[8-10] The PVK is a manually operated emergency shelter ventilation system which consists of a disassembled, bicycle-driven propeller exhaust fan and a collapsed plastic duct, both of which are to be assembled and used by the occupants of the shelter without prior indoctrination. The most significant relationship between the PVK and this project is that it must be assumed that both systems will be operated by similar groups. Of the people tested in the PVK program, most were able to assemble and operate the PVK, using the included instructions. Only a minority, but a most significant minority, were totally unsuccessful. This included one group that assembled and operated the fan without the duct and a number of groups that persisted in operating the fan as an inlet system, which is impossible because the plastic duct would remain collapsed. Partial restrictions in the duct, caused by a combination of improper installation and the tendency for some occupants of the shelter to lean against or even sit on it, were more ordinary operational problems. It would appear that perfectly bright, normal people are quite capable of making rather serious mistakes, and what would seem to be common sense is sometimes an uncommon quality.

A number of observations can be made from the PVK project. First, simple but very serious mistakes, not gross blunders, were made from misinterpreting simple instructions. Second, there exists a potential lack of communication which is difficult to identify when instructions are prepared. That is, what seems obvious to the designer is sometimes quite obscure to the occupants of the shelter. Third, although instructions should be both simple and terse, some effort should be made to explain why the instruction is being given and what will happen if it is not followed. Fourth, every effort should be made to eliminate any procedure which might require that a decision be made by any nonindoctrinated shelter occupant.

Functional Parameters

Chemical Environment. Chemical environmental effects were presented in detail in Reference 1. They are discussed here only briefly and mostly in tabular form. Table 2 lists the effects of oxygen deprivation.[11] Table 3 lists the effects of elevated carbon dioxide concentration.[11,12] It should be noted that neither table presents information about combined effects. It can only be surmised that the deleterious effects of one situation would be potentiated by the other. Table 4 lists the effects of carbon monoxide and is included mainly to stress the requirements for protection against infiltration of the gas.[1] Carbon monoxide is the most significant trace gas and cannot be controlled by ordinary filtration techniques as can odors. In general, odor control is of secondary importance since odors can be tolerated physiologically, their most significant impact is psychological.[13] It should be noted that the olfactory senses adjust and become less sensitive, sometimes even immune, to the same odor upon continuous exposure. The problem tends to seek its own natural solution.

Thermal Environment. The effects of the thermal environment are presented in Table 5.[14] The thermal environment is related to the chemical environment in two ways. First, and most important, the effectiveness of the carbon dioxide absorbent is temperature dependent, becoming less effective as the temperature decreases. At the present time, no solid absorbent is effective below 35°F. Second, as the temperature decreases, the metabolic rate increases. The sensible heat production increases, and the latent heat production and body water dissipation decreases, as shown in Table 6.[15] The chemical environment is bounded, in a sense, by the thermal environment. At low temperatures, the carbon dioxide absorbent is not effective; at effective temperatures exceeding body temperature, life cannot be sustained for long periods of time. Since no power will be available for refrigeration during the sealed period, it may be necessary to precool shelters located in areas which are subject to seasonal extremes of temperature and humidity, as shown in References 16 and 17. It may be necessary to warm shelters which are subject to seasonal internal temperatures below 35°F.[14] It can be shown, however, that this is not a problem for buried structures in general because subsurface soil temperatures drop below freezing only as polar regions are approached and because the metabolic heat load is adequate to warm an unventilated shelter which is insulated.[18]

Table 2. Effects of Oxygen Deficiency

Oxygen Content of Inhaled Air (%)	Effects at Atmospheric Pressure in Otherwise Normal Air
21	Normal air
17	Minimum design concentration for submarines; no prolonged adverse effects
15	No immediate adverse effects
10	Dizziness, shortness of breath, deeper and more rapid respiration, quickened pulse
7	Stupor onset
5	Minimal concentration for life
2 to 3	Momentary death

Table 3. Effects of Carbon Dioxide

Carbon Dioxide Content of Inhaled Air (%)	Effects at Atmospheric Pressure in Otherwise Normal Air
0.03	Normal air
0.5	No adverse effects in 8 hours
1.0	Breathing deeper, slight increase in lung ventilation rate
2.0	Breathing deeper, 50% increase in lung ventilation rate
3.0	Breathing deeper, discomfort onset, 100% increase in lung ventilation rate
4.0	Breathing labored, rate quickened, considerable discomfort, 200% increase in lung ventilation rate
5.0	Breathing extremely labored, severe headaches, nausea onset, 300% increase in lung ventilation rate
7.0 to 9.0	Limit of tolerance
10.0 to 12.0	Loss of coordination, momentary loss of conciousness
15.0 to 20.0	Symptoms increase, probably fatal on hourly exposure
25.0 to 30.0	Diminished respiration, blood pressure drop, coma, anesthesia, fatal on hourly exposure

Table 4. Carbon Monoxide Toxicity

Carbon Monoxide Content of Inhaled Air (%)	Effects at Atmospheric Pressure in Otherwise Normal Air
0.01	Maximum allowable concentration; no ill effects in 8 hours
0.02	Headaches in 2 to 3 hours
0.04	Headaches and nausea in 1 to 2 hours
0.08	Headaches, nausea and vertigo in 3/4 hour; collapse in 2 hours
0.16	Headache, nausea and vertigo in 20 minutes; collapse, unconsciousness, and possibly death in 2 hours
0.32	Headaches and vertigo in 5 to 10 minutes; unconsciousness and danger of death in 30 minutes
0.64	Headaches and vertigo in 1 to 2 minutes; unconsciousness and danger of death in 10 to 15 minutes

Table 5. Thermal Limits for Human Tolerance

Effective Temperature (°F)	Effects on Healthy People at Rest, Properly Clothed
35	Lowest temperature endurable in cold weather for at least 2 weeks in emergencies
35 to 50	Possible chilblain, or shelterfoot
50	Lowest acceptable for continuous exposure; manual dexterity may be affected
68 to 72	"Optimum" for comfort, with 60% relative humidity
78	Perspiration threshold; acceptable for continuous exposure
85	Endurable in emergencies for at least 2 weeks. Possible heat rash in prolonged exposures
88	Possible heat exhaustion in unacclimated people
92	Possible heat exhaustion in acclimated people

Table 6. Metabolic Heat Losses for Sedentary Adults

Dry-Bulb Temperature (°F)	Sensible Heat Loss (Btu/hr)	Latent Heat Loss	
		Btu/Hour	Pound Water/Hour
50	335	65	0.062
60	330	70	0.067
70	300	100	0.096
80	220	180	0.173
90	115	285	0.274
100	0	400	0.384
110	-120	520	0.499

An earth cover, or its equivalent radiation shield, will also serve adequately as thermal insul. tion from a topside firestorm, just as the soil surrounding a buried structure will act as an insulator with respect to heat generated from within. The primary source of heat will be the metabolic heat generated by the occupants of the shelter. The metabolic heat generated (Figure 1) varies with activity and has been assumed to be 400 Btu/hr per person for shelter occupants. The temperature rise resulting from the metabolic heat load will always be beneficial for the solid carbon dioxide absorbents. First, the moisture content of saturated air increases with temperature, and, second, the reaction rate, even for exothermic reactions, increases with temperature. In general, the increase in temperature will benefit the occupants in a cold shelter and will hinder those in a hot shelter, particularly if the initial humidity is high.

Carbon Dioxide Absorbent. Baralyme was selected as the most promising carbon dioxide absorbent (Reference 4) primarily because it is safe for untrained people to handle and to use and because it requires less power input for air circulation. Also, it is cheaper.

Since the air circulation rate has a fixed minimum regardless of the absorbent, the system power requirement is then proportional to the system airflow resistance. The Baralyme system proposed here has a total pressure drop of 0.25 inch of water at 300 cfm. A comparable lithium hydroxide system using Navy cannisters would have a minimum pressure drop of 1.5 inches of water at 300 cfm, thereby requiring 6 times the power input.[19,20]

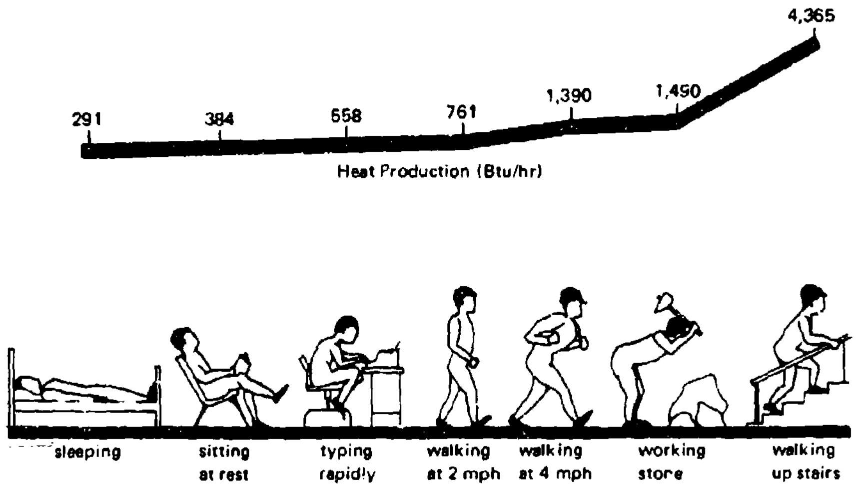


Figure 1. Heat production of the human body from various activities.

A review of the literature revealed that, until the Navy cannister was developed by the Naval Research Laboratory, the use of lithium hydroxide aboard submarines was tenuous at best. The development of the cannister alleviated most of the inherent dusting and caking problems associated with the absorbent.[19] If lithium hydroxide were to be used in a shelter air revitalization system, it was deemed inadvisable to deviate from the use of the cannisters, and the absorbent was evaluated on that basis. A sealed survival shelter is not a submarine. A submarine has a trained crew and, even if disabled, has a limited power supply. It cannot be assumed that shelter occupants will be trained or even particularly well disciplined. In addition, there will be no power available. The distinction between limited power and no power cannot be overemphasized. Because lithium hydroxide is the obvious absorbent for submarines—it weighs less, requires less space, and reacts more rapidly—it does not necessarily follow that it is the obvious absorbent for shelters.

Circulation power requirements are a function of absorbent efficiency and effectiveness. Absorbent efficiency, strictly defined, is the ratio of the amount of carbon dioxide which is absorbed to the amount of carbon dioxide which can be absorbed theoretically. Absorbent effectiveness will be used here as a rough indication of absorbent efficiency as a function of time.

Assuming a constant circulation rate, the power requirement is proportional to the absorbent bed pressure drop. Bed pressure drop can be lowered by decreasing bed thickness and by decreasing superficial velocity. Superficial velocity is the influent gas velocity determined by the gasflow rate and the cross-sectional area of an open bed. It is the velocity the gas would have if the absorbent granules were not in place; it is not the velocity of the gas flowing around or between absorbent granules.

Both the high and low temperature behavior of the absorbent were questioned and were subsequently evaluated.[4] An initial shelter temperature of 30°F to 35°F is compatible with the use of Baralyme because subsurface soil temperatures below freezing are encountered only as polar regions are approached,[21] and because there is a significant temperature rise from metabolic heating within a sealed habitat which is buried. For example, a winter shelter habitation test involved sealing the shelter for the first 3-1/2 hours of occupancy, during which time the temperature increased from 52°F to 69°F.[5] Furthermore, a delay exists between the time the shelter is sealed and the time the addition of oxygen and the removal of carbon dioxide are required. These delays can be estimated from Figure 2.

A number of conclusions and observations can be made from the work reported in Reference 4.

1. The optimum absorbent bed depth with regard to both pressure drop (that is, power requirement) and overall effectiveness was found to be nominally 5 inches.

2. The nominal pressure drop across the absorbent bed was 0.05 inch of water with a superficial velocity of 7.5 fpm.

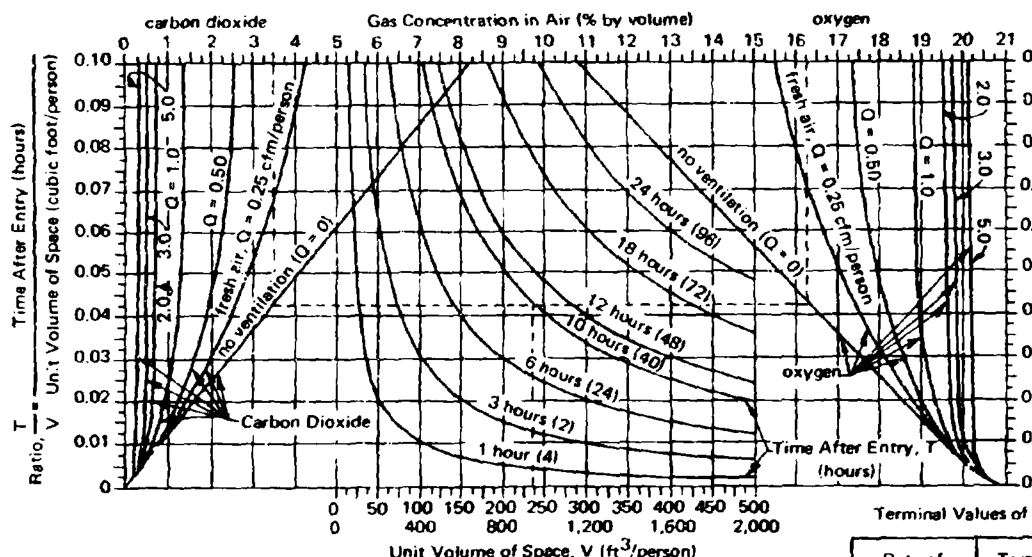
3. The superficial velocity must be as low as possible if absorbent effectiveness is to be maintained. In short, the flow rate through the absorbent should not be increased if power is available to operate a fan of any capacity.

4. The reaction efficiency of Baralyme is time dependent and increases with time.

5. The reaction efficiency increases disproportionately with contact time, as determined by absorbent bed depth and superficial velocity.

6. Water, which is essential for a sustained reaction, can be provided by the liberation of hydrated water, by the reaction with carbon dioxide, by the respiration and perspiration of the shelter occupants, or by a combination of these.

7. Reaction efficiency is temperature dependent, presumably because the moisture content of saturated air decreases with temperature.



Note: The example indicated by dotted lines shows that a carbon dioxide concentration of 3.50% by volume will develop in 10 hours in an unventilated shelter having a net volume of 235 ft^3/person and that the oxygen content of the air will then be 16.25% by volume.

Physical Data

- Oxygen consumed—0.90 cubic foot/hr/person
- Carbon dioxide produced—0.75 cubic foot/hr/person
- Moisture loss from body—0.144 lb/hr/person
- Oxygen in fresh air—20.62% by volume
- Carbon dioxide in fresh air—0.03% by volume
- Dry-bulb temperature—77°F = 25°C
- Relative humidity of fresh air—50%
- Barometric pressure—760 mm of Hg

Terminal Values of Gas Concentration

Rate of Ventilation	Terminal Concentration (% by volume)	
(cfm/person)	Carbon Dioxide	Oxygen
0.25	5.35	14.13
0.50	2.67	17.23
1.00	1.35	18.77
2.00	0.69	19.83
3.00	0.47	19.79
5.00	0.29	20.11

Figure 2. Predicted concentrations of carbon dioxide and oxygen with time in shelter atmospheres from human metabolism (from Reference 14).

8. Baralyme, because it contains hydrated water which is freed to enter the reaction with carbon dioxide, is less temperature dependent than other $Ca(OH)_2$ based absorbents which are not effective below 65°F.

9. The low temperature limit of Baralyme varies from 35°F to 50°F, depending upon which of the chemical constituents of the absorbent are active during the varying phases of the reaction.

10. The absorption rate of Baralyme, although slow, is nearly constant. The carbon dioxide concentration increases abruptly only when the absorbent is spent, the influent carbon dioxide rate is increased excessively, or the lower temperature limit is exceeded.

11. Baralyme approached its theoretical absorption capacity during both the recirculation and cold chamber tests, where contact time and superficial velocity were optimized.

DESIGN CRITERIA

It is assumed that the basic design criteria for a shelter will include some level of blast, radiation, biological, chemical, and fallout protection. It is also assumed that the total period of occupancy will be at least 2 weeks, during which time the chemical and thermal environment will be controlled by ventilating air which can be heated, cooled, and filtered as necessary. External power, either emergency or commercial, will be available. When a shelter is sealed, presumably because of a topside firestorm, chemical environmental control conditions which are peculiar to that situation and no other exist, and suitable design criteria must be fixed. In addition, requirements for a specific air revitalization unit must include intrinsic assumptions, capacity for example, which are included in design criteria. The following criteria, although arbitrary to some extent, are based primarily on NAVFAC specifications from Reference 5:

1. There will be 100 shelter occupants.

2. The button-up period or sealed period will be 24 hours.

3. There will be no external power supply. This includes emergency diesel generators which are assumed to be inoperable during firestorms.

4. The power to operate the unit should not exceed 0.03 hp.

5. The selection of the type of structure is not essential as long as factors influencing the chemical environment are considered. This includes adequate insulation from the external thermal environment and provisions for minimum space requirements for the occupants of the shelter. The free volume, that is, the total volume less the volume of personnel and equipment, will be assumed to be approximately 8,000 ft^3 with an inner surface area of approximately 3,000 ft^2.

6. The oxygen consumption rate will be 1.0 ft^3/hr/man.[22] This assumes that the occupants of the shelter will be average men at rest or doing light work. It is assumed that the carbon dioxide level will be controlled to the extent that shelter occupants will not hyperventilate and, therefore, waste oxygen with an increased metabolic rate.

7. The carbon dioxide production rate will be 0.85 ft^3/hr/man, which is based upon a respiratory quotient of 0.85 and the aforementioned oxygen consumption rate. The respiratory quotient is the volume fraction of carbon dioxide produced to oxygen consumed. It can vary from 0.45 to 1.0, depending on diet. A value of 0.85 is assumed for normal diets. It should be noted that the respiratory quotient does not vary appreciably when a person does not eat because the body continues to consume stored fat and tissue at a relatively constant rate.[22]

8. Oxygen will be supplied at the rate at which it is used, and the concentration will not be allowed to drop below 20% to 21% with normal respiration. From Table 2, it can be seen that lower concentrations can be tolerated. For non-nuclear submarines, which submerge for only a few hours at a time, the limiting concentration is 17%.[22] For the sealed shelter described here, there is little economy to be realized with the lower concentration. To be specific, if the concentration is allowed to drop from 21% to 15%, the volume of stored oxygen can be reduced from 2,500 scf to 2,000 scf. This is the storage capacity of two standard pressure cylinders. Potential restrictions resulting from supplying the minimum oxygen requirements include no possibility of shelter population increase, no possibility of an extended button-up period, no work potential from the shelter occupants—in short, no factor of safety.

9. The design carbon dioxide concentration should not exceed 1% in order to maintain reasonable comfort and well-being as shown in Table 3. For a 24-hour period, the concentration can be increased to 3% before severe discomfort and hyperventilation occur. Design criteria for submarines vary from 1% concentration on nuclear submarines to 3% for conventional battery-powered submarines.[22]

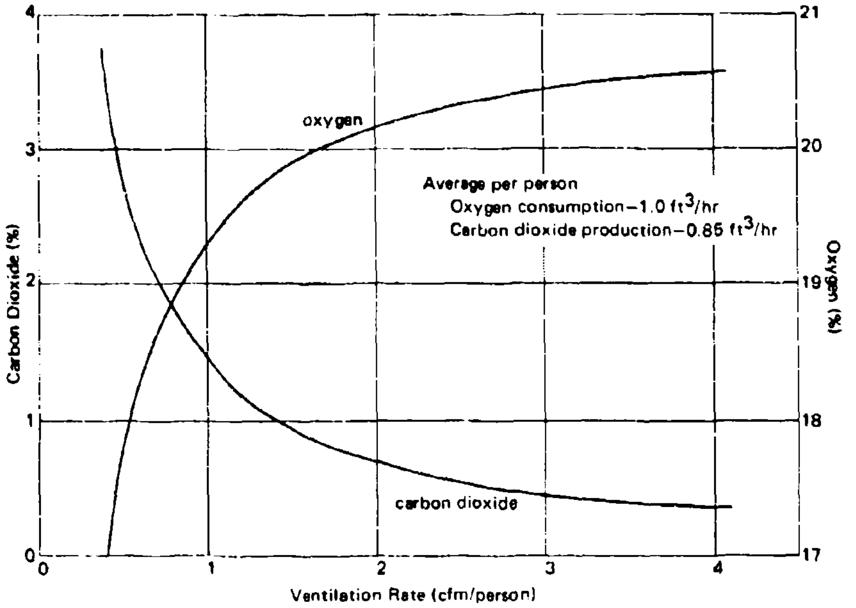


Figure 3. Steady-state concentrations of carbon dioxide and oxygen in shelter atmospheres as a function of ventilation rate.

10. The air circulation rate within the shelter will be 3 cfm/man. This value is based upon the minimum fresh air ventilation rate for chemical environmental control as shown in Figure 3.[22] It should be noted that the maximum airflow rate through the carbon dioxide absorbent should not exceed 300 cfm in order to maintain absorbent efficiency.

11. The metabolic heat input rate is assumed to be 400 Btu/hr/man for an average shelter occupant at rest (Figure 1). The heat rate will increase with physical exertion and with a decrease in ambient temperature.[15]

12. The initial temperature in an unconditioned shelter depends primarily on soil temperature. Soil temperature than sets the lower limit at approximately 35°F since freezing a few feet beneath the soil surface does not occur within the continental United States. The upper limit is set by the endurance level of the shelter occupants. The result is an overall range of 35°F to 90°F.[14]

13. Human factors must be considered within the framework of design criteria. The role of a protective shelter, operational or otherwise, is not well defined. It is possible that both civilian and military personnel will be scheduled as NAVFAC shelter occupants. This permits a possible age range

of 18 to 70 years. The prediction of physical conditions and state of health is equally difficult. In short, physiological factors cannot now be estimated with any degree of certainty and must, therefore, be treated conservatively and circumvented, if possible. Similarly, discipline within the shelter, general preparation prior to shelter occupancy, and basic indoctrination and familiarization with survival equipment within the shelter must also be treated conservatively at the present time. A piece of hardware designed for future applications, which have not been enumerated, must be operable under many conditions, if it is to be effective.

14. In general, operational and functional parameters were given precedence over economic parameters. Of the economic parameters, cost was considered first, space second, and weight third. Individual components were designed to facilitate installation. The total volume of the assembled unit was minimized within the constraints of airflow resistance and power requirement.

15. Potential shock loading from blast-induced ground motion was not considered. It was assumed that the tolerable overpressure would vary considerably with the individual shelter. In addition, ground motion is a function of both air-blast effects and soil structure. Appropriate shock isolation techniques should be employed, depending on the requirement of the shelter.

16. Odors and trace gas control are of secondary importance. Odor control will be effected because odor removal is neither difficult nor costly and will probably provide some positive psychological effect. Odors, although sometimes unpleasant, cause only transitory physiological effects, if any. For example, nausea can be odor induced. In addition, the olfactory senses adjust and become less sensitive on continuous exposure to the same odor.[13]

17. Because the trace gas problem can be readily circumvented, neither mechanical nor chemical control will be attempted. The most common trace gasses are carbon monoxide and hydrogen. There are two primary sources of carbon monoxide, infiltration and smoking. If the shelter is properly designed, infiltration will not be a problem. Although cigarettes do not produce an intolerable carbon monoxide level,[1] a simple smoking curfew while the shelter is sealed would eliminate both carbon monoxide and a primary odor source. Hydrogen, on the other hand, presents no physiological hazard, but is readily combustible and will explode if general or localized concentration is allowed to build up. Batteries should be the only hydrogen source of any consequence within the shelters. Whatever battery power is required for the internal operation of the shelter, lighting, for example, will not produce hydrogen in dangerous quantities since only 0.083 pound of hydrogen is liberated per 1,000 ampere hours.[23] If a significant hydrogen

or other trace gas source is unavoidable, then the gas must be removed by venting, by controlled combustion, or by catalytic oxidation with Hopcalite or some other agent.[14,19] This is, however, a problem for the designer of the shelter.

18. The prototype unit is designed for a storage life of 20 years. The unit is designed for possible storage in a damp or otherwise corrosive environment. Metal components are either corrosion resistant, provided with protective coatings, or sealed in such a manner as to render the environment innocuous. Nonmetallic components are similarly protected.

DESCRIPTION AND SPECIFICATION

A prototype air revitalization unit was designed and fabricated from Government specifications and design criteria by the Ben Holt Company. The unit is shown in Figure 4 and in the Appendix (drawings 70-27-1D through 70-27-6D). The prototype is capable of supplying oxygen to and removing carbon dioxide and noxious odors from a 100-man habitat continuously for a period of 24 hours. No external power is required to operate the unit. Air circulation through the unit is accomplished by a battery-powered motor driving a fan located on the downstream side. Under actual operating conditions, carbon dioxide is absorbed by a dry chemical absorbent in a parallel bed arrangement, with noxious odors being absorbed by an activated charcoal filter. Oxygen is supplied from standard oxygen pressure cylinders. Two hinged air distribution plenums separate the absorbent trays from the fan on one side and the charcoal filter on the other side. The upstream plenum is designed to evenly distribute the air passing through the absorbent trays. The downstream plenum collects the air from the trays for distribution to the fan.

The total weight of the unit, including the absorbent trays when filled, is less than 2,000 pounds. The unit is capable of being dismantled into four or more components to allow movement through personnel access passages with right-angle turns and doglegs and through openings which are 2 by 4 feet. The weight of each component is less than 400 pounds for ease of handling during installation. The hot dipped glavanized frame and trays are enclosed by galvanized sheet to provide corrosion resistance for the 20-year design life.

Carbon Dioxide Absorbent System

Baralyme was selected as the most promising carbon dioxide absorbent for survival shelter applications. The theoretical absorbent capacity is 0.503 pound of carbon dioxide per pound of Baralyme or 29 pounds of

carbon dioxide per cubic foot of Baralyme. The density of 4-to-8-mesh granular Baralyme is 58 lb/ft^3. The cost per pound is \$0.37 in quantities of 2,000 pounds or greater. The material is packaged in 2-pound cartons and 5 gallon tins and is available only through National Cylinder Gas, a division of Chemtron Corporation. The ambient operating temperature range, according to the manufacturer, is approximately 35°F to 212°F. At 212°F, the molecules of water of crystallization start to lose their bonds. The shelf life of the absorbent is 4 to 7 years in the 2-pound carton and indefinite in the 5-gallon tins when stored at temperatures below 100°F. The granules are resistant to erosion and fragmentation during storage. Superficial dusting is controlled by an added wetting agent. The granules possess a high degree of porosity and permeability to gases. This permits the use of relatively large granules, 4 to 8 mesh, which lowers the pressure drop of gases passing through an absorbent bed. A dye is added to indicate absorbent effectiveness during usage. Unused absorbent is pink; the color changes to blue or purple with use.

Twenty-four absorbent trays were placed for use as shown in Figure 5. The internal unobstructed dimensions of each tray are 12 inches wide by 20 inches long by 6 inches high. Each tray is equipped with four carrying handles and is capable of being readily removed and replaced in the unit. For design purposes, 40 pounds of Baralyme, the contents of one 5-gallon tin, is placed in each tray. The bottom of the trays consist of 16-mesh hardware cloth supported by an expanded metal grid. The vertical distance between trays is 6 inches. Two trays, end to end, are placed three abreast on four racks in two separate sections. A metal frame supports the trays. An airtight metal housing encloses the entire unit.

Oxygen Supply System

An oxygen supply and distribution system was designed for a 24-hour requirement of 2,500 scf. Pressure cylinders were selected as the oxygen supply, primarily because they are safe and easy to use. Human factors associated with untrained people governed the choice. The use of pressure cylinders involves only two steps, opening a stop valve and setting a single two-stage pressure regulator to meter flow through a flowrator. In addition, the use of ten standard 250-ft^3 oxygen pressure cylinders is preferred because such cylinders are readily available from any commercial vendor. The oxygen enters the shelter through a diffuser–duct arrangement on the downstream side of a circulation fan as shown in Figure 5. Thorough mixing of the air and oxygen is essential not only for the general supply to the shelter but also for the prevention of a fire hazard should oxygen-rich pockets exist. As an added safety measure, when the pressure regulator is set, a pressure switch in the oxygen supply line turns on the fan.

(a) Inlet view.

(b) Outlet view.

Figure 4. Prototype air revitalization unit.

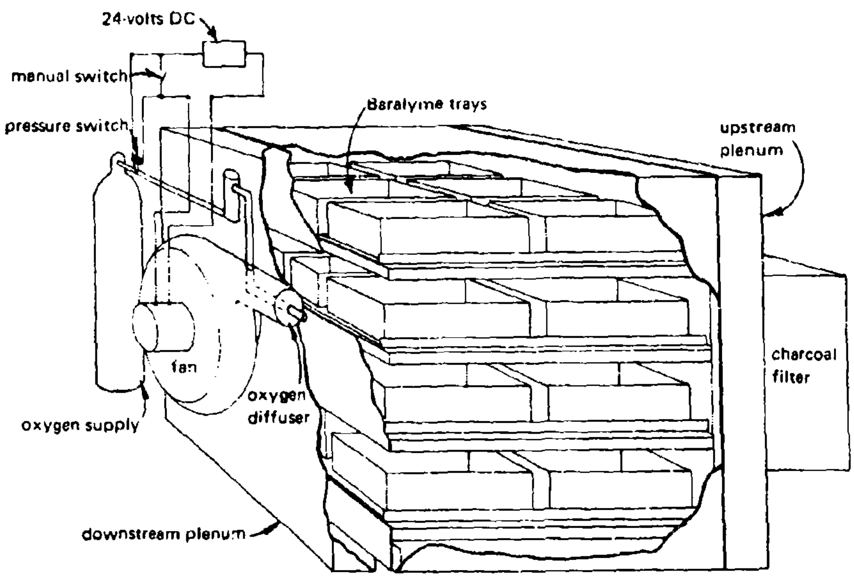


Figure 5. Schematic of air revitalization unit.

Odor Removal System

A charcoal filter was selected for odor removal. In order to minimize airflow resistance, an oversized filter was used. For example, if a filter sized for a 1,000-cfm flow rate is used with a 300-cfm flow rate, the nominal pressure drop is 0.05 inch of water. The charcoal filter is located on the upstream side of the unit. Past investigations indicate that contaminated activated charcoal will ignite spontaneously in a normal atmosphere at temperatures as low as 360°F.[12,24] Although activated charcoal is not readily ignited, it does deserve to be treated with respect as a fire hazard. With this in mind, the oxygen supply outlet and the charcoal filter were located on opposite ends of the unit as far away from each other as possible. It was assumed that an increase in oxygen concentration would potentiate any fire hazard, spontaneous ignition or otherwise.

Air Circulation

Air is circulated by a battery-powered centrifugal fan. The motor is a 24-volt, enclosed, permanent magnet type. A Clarage Type HV No. 5/8 fan, whic 60% efficient, is used. This fan was selected because similar

fans of this capacity are nominally 40% efficient. The efficiency of electric motors also varied considerably. In addition, the belt between the motor and the fan must be carefully selected to minimize drag loads. Bates Polyflex belts and pulleys with a 5M width are recommended. The fan may be turned off or on manually unless oxygen is being supplied, at which time, the fan is on continuously.

Stand-By Power System

A commercial stand-by power system manufactured by the Surrette Storage Battery Co., Inc. which uses lead–acid batteries and which will remain on trickle charge for 10 to 15 years with only yearly maintenance was selected. Catalytic vent caps are used to recombine the hydrogen and oxygen emitted by the battery during charging. Thus battery water is conserved, and the hazard associated with the emission of hydrogen and oxygen within a confined space is minimized. An enclosed battery rack was provided to house the four 6-volt storage batteries. The rack is constructed to be attached to one side of the air revitalization unit. The enclosure was designed to facilitate easy access for servicing and charging of the batteries. Suitable switches and wiring were provided. The switches include a pressure switch and a manual switch. The pressure switch should have a minimum activation pressure of 1.0 psi and is installed in the oxygen line downstream from the pressure regulator and upstream to an orifice union.

Cost

Component cost, although not an overriding parameter, was considered. Fortunately, many of the components selected on functional bases were also the least expensive. Table 7 presents the estimated cost and is based on prototype unit fabrication costs.

PROTOTYPE EVALUATION

Test Program

It was assumed that the unit would be handled by untrained and trained personnel. The untrained group would cope with the problems of loading and operating the unit without benefit of prior instruction during an emergency. The trained personnel would maintain the unit so that it could be used with minimum difficulty during emergency situations. Therefore, the unit was evaluated experimentally for use by trained and untrained personnel as well as for chemical, mechanical, and structural performance.

Table 7. Cost Estimates of Components

Item	Manufacturer	Model	Cost ($)
Absorbent[a]	–	–	360
Oxygen[b]	–	–	650
Motor	Globe Industries, Inc.	166A100-10	110
Fan	Clarage Fan Co.	5/8 HV 1500-AQ	130
Batteries[c]	Surrette Storage Battery Co., Inc.	HG-100	200
Battery charger	Motor Appliance Corp.	1444T	150
Belts and pulleys	Gates Polyflex	SM	15
Orifice	Daniel Industries, Inc.	–	20
Oxygen manifold	Matheson	–	375
Pressure switch	–	–	20
Pressure regulator	Matheson	8-540	60
Block valve	Rego	9500A	40
Charcoal filter	Barnabey-Chaney	FMD	310
Flowmeter	Fischer & Porter Flowrator Tube Metering float	3565 FP 1/2021-G-10 1/2-G-SVT-45A	80
Frame and enclosure[d]	–	–	1,000
Total			3,520

[a] 960 lb at $0.37/lb.

[b] Ten cylinders.

[c] Four at $49 each.

[d] Estimated for 100 units.

The test program was divided into two phases. The first phase included testing various components separately (for example, the battery charger) and checking pre-operational functions of the unit (for example, assembly and disassembly, ease of tray loading and accessibility). The original phase two test plan included a 24-hour continuous operation test of the integrated system. An integrated test program would have been considerably more definitive, since possible interaction among functions and components could have been observed. It was, however, necessary to abandon the integrated test, but major components were tested continuously for 24 hours.

Test Setup

The unit was installed in an 8 x 11 x 15-foot sealed test chamber (Figure 4b). Carbon dioxide was to be produced when a metered oxygen supply was consumed by a bank of propane fed catalytic burners. Catalytic burners were selected because they produce only carbon dioxide and water as products of combustion because of their low combustion temperature. In addition, the low temperature flame would make the burners quite safe to use. In short, it would be relatively simple to simulate human respiration. Unfortunately, the burners were lost in shipment, and a company strike which followed precluded their use within the time frame of the test. An open flame burner system was considered but was discarded because it would produce a contaminated gas mixture and create a fire hazard. The usefulness of such a gas mixture would be doubtful since the constituents—carbon dioxide, carbon monoxide, hydrocarbons, and water—would require constant monitoring and would generally be suspect.

In lieu of the proposed phase two test, the major components were tested separately by function. Oxygen flow metering was checked with a flowrater and weigh scale. Oxygen mixing was checked qualitatively by spraying dust into the gas inlet for the diffuser duct. The absorbent section, including battery-operated fan and charcoal filter, was tested in a sealed test chamber into which a predetermined carbon dioxide flow based on respiratory quotient and number of occupants was discharged. The unit and the room were extensively instrumented. A thermocouple was buried in each of the 24 absorbent beds as shown in Figure 6. Since the absorbent reaction is exothermic, the relative activity of each bed can be monitored readily, and information such as any anomalies among air distribution patterns through the absorbent beds can be obtained. In addition, four thermocouples were placed randomly about the room, a fifth was located near the unit inlet, and a sixth was located in the flow path from the unit outlet. This group would (1) indicate the existence of temperature gradients in the room and (2) be a relative indicator of gas mixing since the air leaving the unit should be warmer than that entering the unit because of the reaction within. Another thermocouple was affixed to the fan motor along with a volt meter and ammeter to measure performance. A final thermocouple was located in the room surrounding the sealed test chamber. It was assumed that chamber temperature would be a function of the outside temperature because of heat transfer through the chamber walls.

Relative humidity within the chamber was measured because the carbon dioxide reaction with Baralyme is sensitive to airborne water. A Hygrodynamics Electric Hygrometer-Indicator, Model 15-3001, was used to measure the relative humidity.

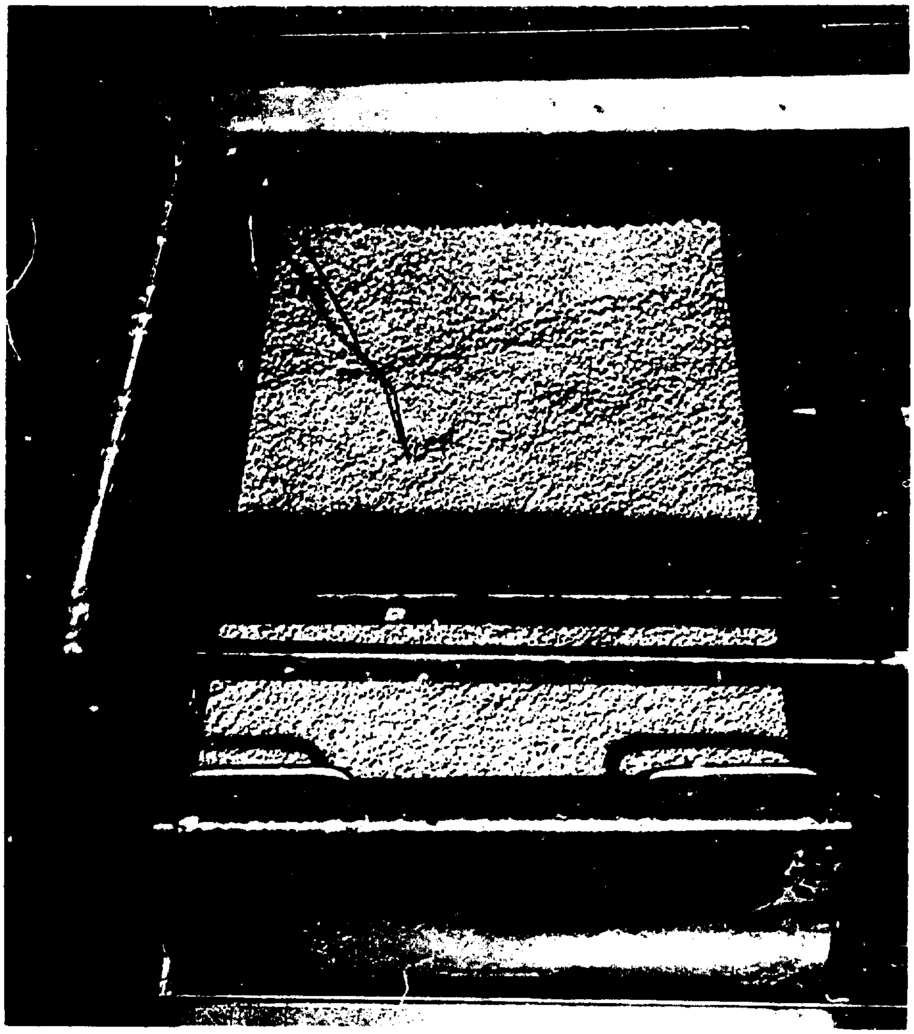


Figure 6. Filled absorbent tray with thermocouple lead in place in the unit.

Two pressure measurements were taken. The first indicated flow resistance across the absorbent section, while the second indicated velocity head in the fan outlet duct. These measurements were taken for two reasons. First, since the fan is battery-powered, its performance should degrade with time. Second, the flow resistance of the Baralyme bed increases as the reaction progresses. This change in the material is observed as a formation of a hard top crust and is presumably caused by the exposure of the absorbent to water vapor.

Carbon dioxide input was metered through a flowrater and checked with a balance scale. The carbon dioxide bottle was simply set on the scale and weighed before it was opened, periodically while it was emptying, and when it was empty. The carbon dioxide concentration in the sealed chamber was determined by two Orsat type carbon dioxide indicators, specifically, F. W. Dwyer 0-5% CO_2 Indicator, Model G57-1-432. Two indicators were used in order to establish data credibility.

Required Data

Two types of data were required, performance and environmental. The capability of the unit to remove carbon dioxide and to add oxygen, in other words, to control the chemical environment, is the primary measure of performance. Performance is a function of the environment in which the unit operates and, therefore, must be measured. For example, carbon dioxide absorption is enhanced by elevated temperatures, carbon dioxide concentration, and relative humidity. A performance test, to be meaningful, must therefore be conducted in an environment which is within the bounds of human tolerance.

However, a most significant part of performance data is concerned with how amenable this device is to successful operation—from installation and maintenance to emergency use. Such data are generally qualitative. It is, for the most part, compiled from observations and, unfortunately, is subjective.

TEST RESULTS

Phase One

Following fabrication of the unit the contractor performed a number of tests to determine if contract specifications had been met. These included a soap bubble test for external leaks, flow resistance tests across the absorbent section, and a power requirement test. All but the latter were affirmative. It was found that the 1/2-inch-wide V-belt between the reduction gear and the fan caused excessive drag. The belt and pulleys were replaced with a 5M width Gates Polyflex belt system, and the unit then performed satisfactorily.

A rather conspicuous flaw appeared in the unit when it was disassembled at NCEL. The baffles or panels, which route air around the absorbent trays, were bolted to the absorbent section of the unit. In such a position they would be difficult to remove in order to load the trays during emergency use.

It was concluded that they should be moved to the plenum/door where they could be permanently placed, would not hinder unit operation, and would stiffen the plenum/door structure. Accordingly, the Appendix drawings 70-27-5D and 70-27-6D were changed. During assembly it became apparent that to use bolts and nuts to fasten the plenum/door to the absorbent section was rather cumbersome and not in keeping with the untrained operator design consideration. A system of latches was selected to replace this arrangement. This modification is shown on drawing 6807-3.

Following the initial disassembly/assembly check, the unit was again disassembled and moved to a sealed test chamber. The disassembled unit was passed through a 26-inch-wide door and reassembled inside without incident.

The batteries to power the unit were filled with fluid and brought up to full charge. They were discharged for 24 hours across a known resistance which simulated the fan motor load. The results are shown in Figure 7. Since this check was successful, the batteries, battery charger, and fan motor were connected. Two problem areas were noted. The batteries would discharge through the charger when it was not operating, and there were two charging voltages, 27 volts and 38 volts. The fan motor ran nicely on 27 volts, but it would not accommodate a 38-volt input. Originally it had been planned to power the fan motor through the battery charger when 110-VAC power was available. It had also been planned to leave the charge connected when 110-VAC power was not available and the motor was on battery power. Neither was possible, and the most direct approach was simply to take the charger off the line at those times.

Fan speed was checked and was found to be 870 rpm, which was high but acceptable for the battery-powered situation. It was assumed that speed would be lower with older or partially discharged batteries. It should again be noted that even if power is available the superficial velocity through the absorbent must not be excessive or absorbent efficiency will drop. It was found that the reduction gearbox was very noisy. The contractor was notified. A similar observation had previously been made by the contractor who had contacted the manufacturer and was assured that the noise was typical. However, the tone and noise level was most annoying, and it was concluded that the gearbox arrangement would not be acceptable for shelter use.

The oxygen supply system was checked for flow rate and dispersal. The experimentally determined flow through the metering orifice was plotted along with the contractor's calibration curve in Figure 8. Oxygen mixing with air and subsequent dispersal was checked by injecting powdered chalk into the diffuser—duct section on the downstream side of the fan. Photographs of the dispersal pattern are shown in Figure 9. From these patterns it was concluded that mixing would be adequate. The fan motor pressure switch was tested. The minimum trip level was found to be 24 psi; from Figure 8 it can be seen that 24 psi represents a considerable flow rate. It was concluded that this switch was inadequate for its intended use.

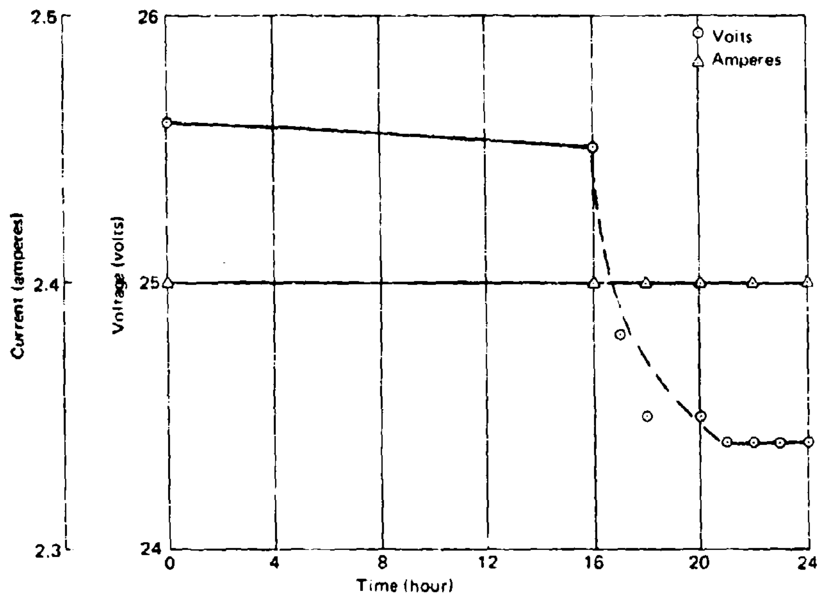


Figure 7. Test results for battery discharge.

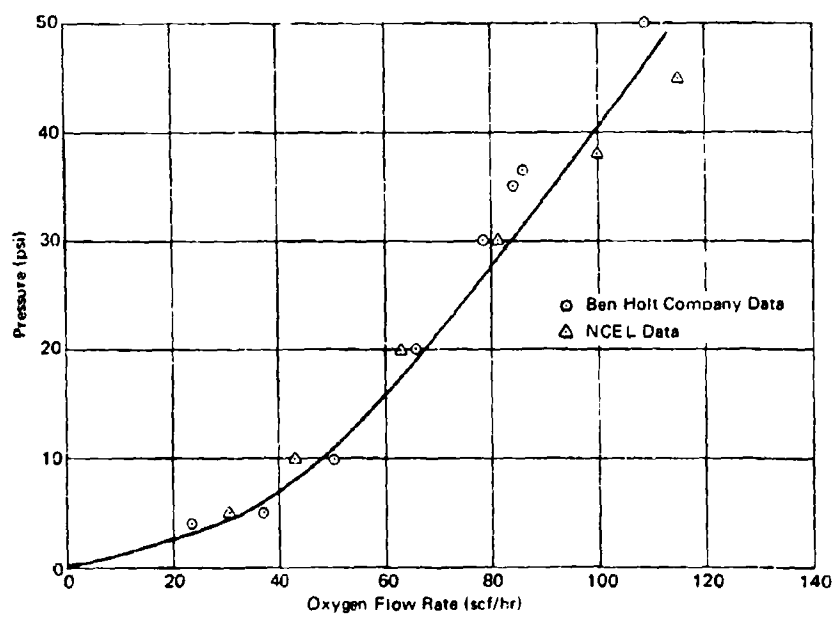
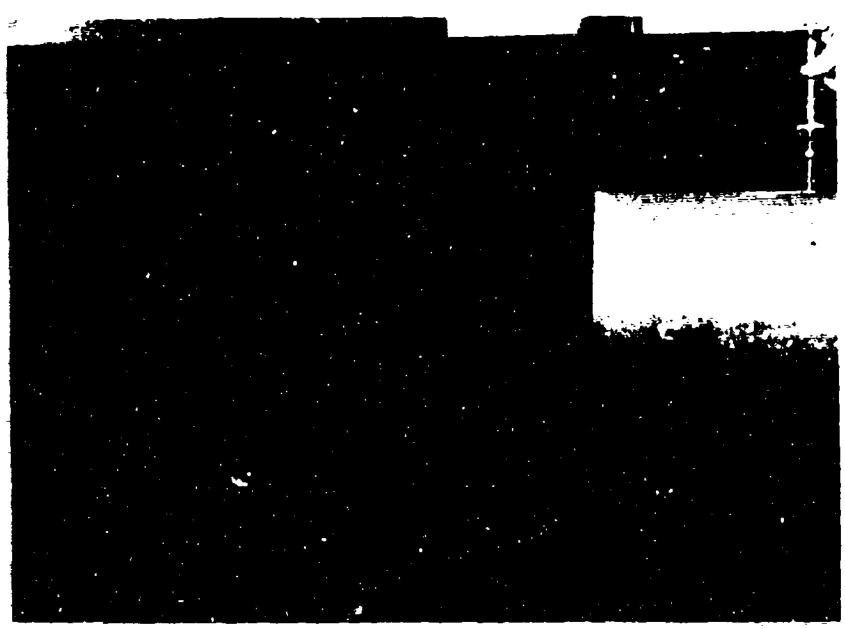


Figure 8. Orifice calibration curve.

(a) During formation.



(b) Fully developed.

Figure 9. Chalk dust dispersal pattern.

Phase Two

During the phase two test, two men loaded the unit with 960 pounds of Baralyme (twenty-four 40-pound cans) in 2 hours without effort. The loading operations are shown in Figures 10 and 11. A number of potential problem areas were noted, however.

Baralyme trays must be properly oriented before they are inserted. Admittedly, it would be awkward to install a tray backwards, but it is possible. Each tray has a pair of lugs or cams mounted on the sides at the forward end which slide along rails. The lugs permit the tray to slide into place before settling onto the soft foam gasket beneath it. If the tray is slid backwards, the gasket material could be damaged, and the tray would not seat properly.

Sharp edges were encountered which should either be broken off or be covered with a protective material.

When the unit was loaded, the structure deformed slightly. Since the plenum doors had not been converted to latch shut, they were difficult to close. The bolt pattern in the door did not change while that on the absorbent section deformed slightly.

The 24-hour test was started at 1545 on 8 April 1969. The test proceeded without incident for some 13 hours until 0450 on 9 April 1969. At this time the speed reducer failed. The disassembled gearbox is shown in Figures 12 and 13. The failure was due apparently to gear tooth wear which was precipitated by operating at speeds higher than recommended. However, it should be noted that, although the gearbox was operating at 30% over-speed, it was only operating at 5% of the rated torque, 500 in.-oz. It was concluded that the best solution was to use a slower speed motor and effect speed reduction with belt pulley sizes, thereby eliminating the noisy and troublesome gearbox.

The test was restarted at 0600 on 9 April 1969. The 24-VDC fan motor and gearbox were replaced by a 110-VAC motor. Fan speed was somewhat slower at 750 rpm, but it was adequate to continue the test.

The test results are shown on a 24-hour time scale in Figures 14 through 17 and in Tables 8 and 9. Key data are the carbon dioxide concentration level which reached a maximum value of 0.7% after 15 hours. For a respiratory quotient of 0.85, the carbon dioxide input would be 85 scf/hr for a 100-man simulation. The average input during the test was 82 scf/hr which, although low, is acceptable within experimental error.

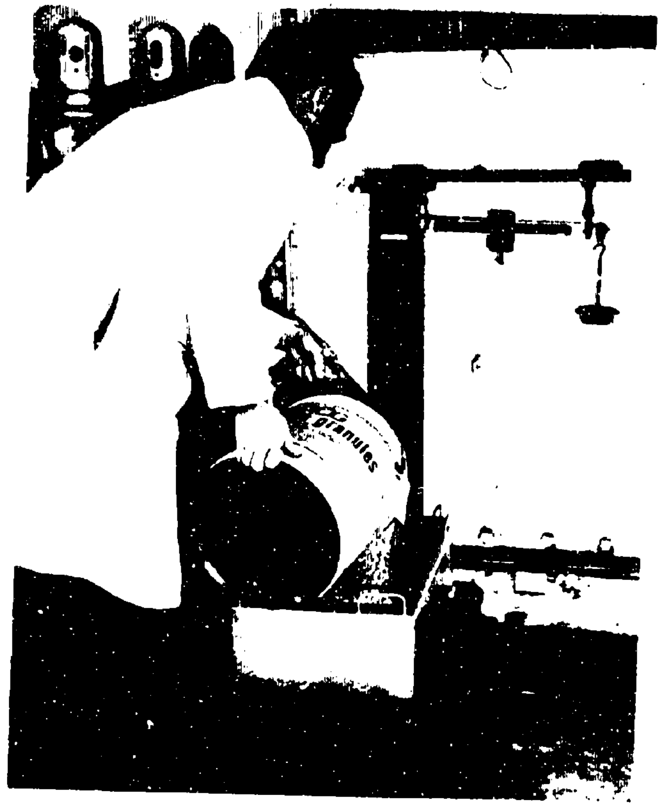


Figure 10. Absorbent tray being loaded with Baralyme.

Figure 11. Absorbent tray being placed in the unit.

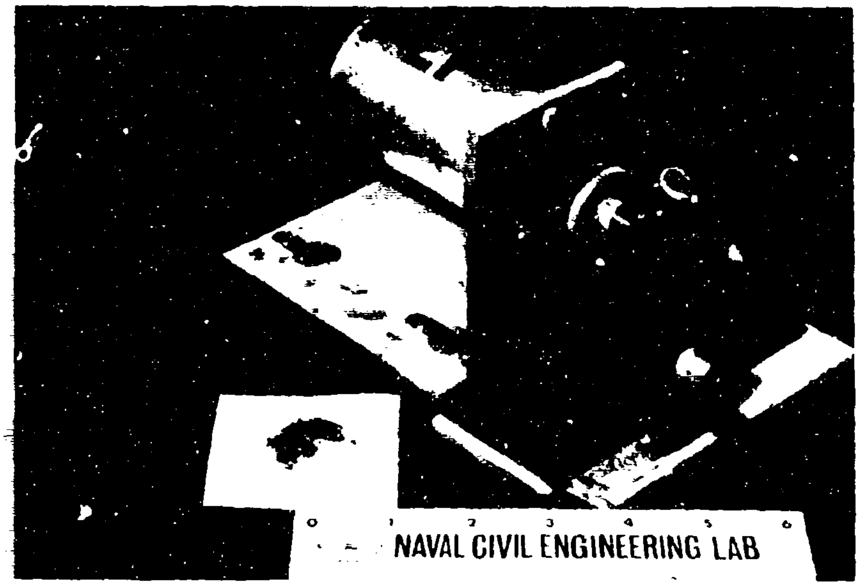


Figure 12. Motor with broken speed reducer.

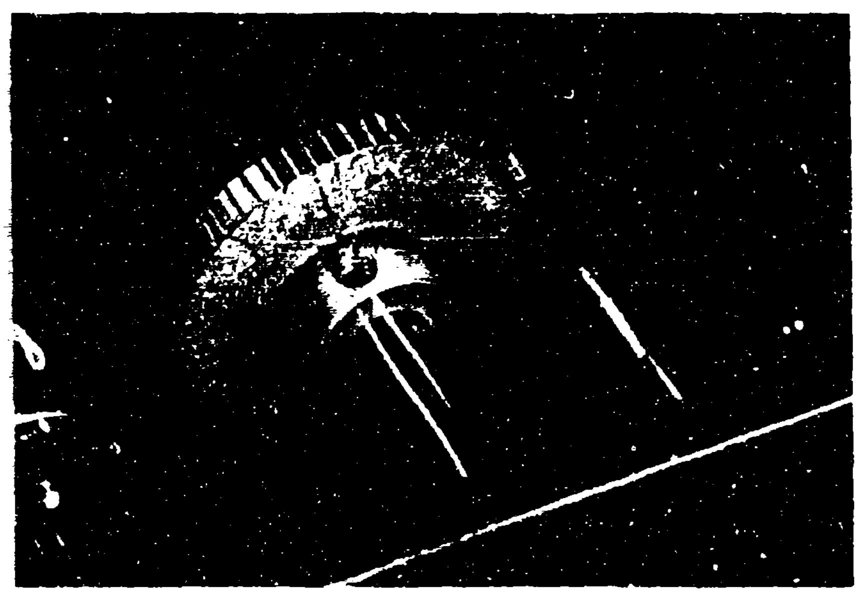


Figure 13. Stripped spur gears in speed reducer.

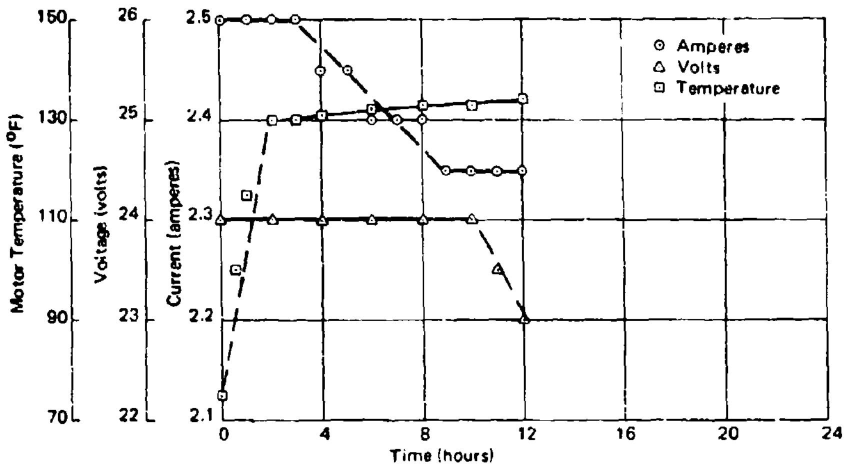


Figure 14. Test results for electrical system performance.

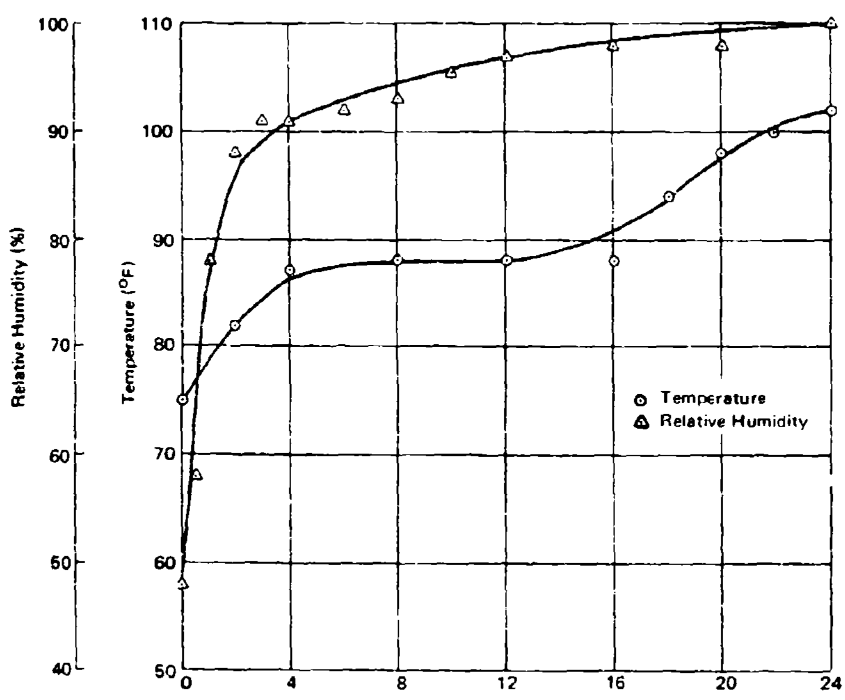


Figure 15. Test results for chamber environment.

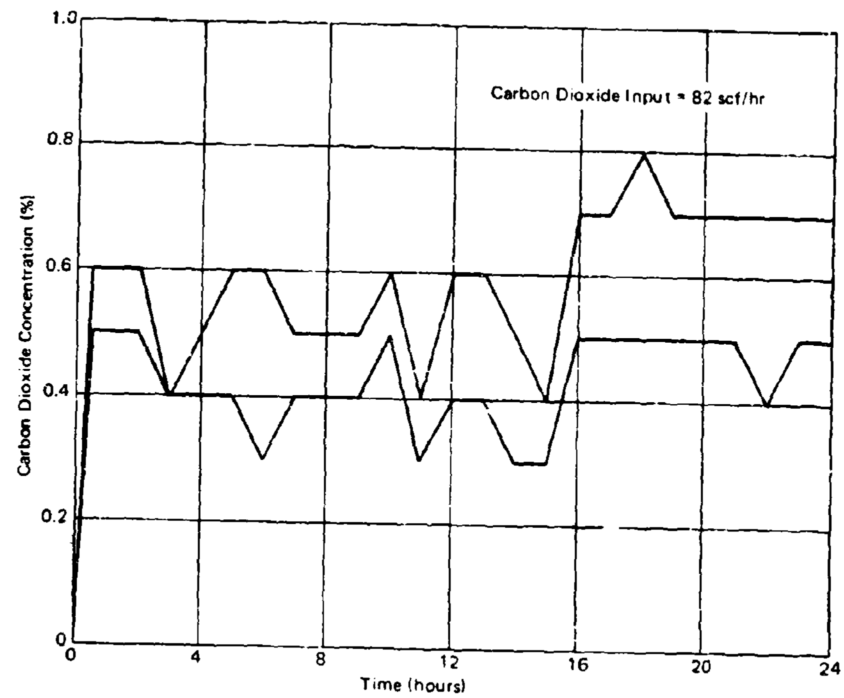


Figure 16. Test results for absorbent performance.

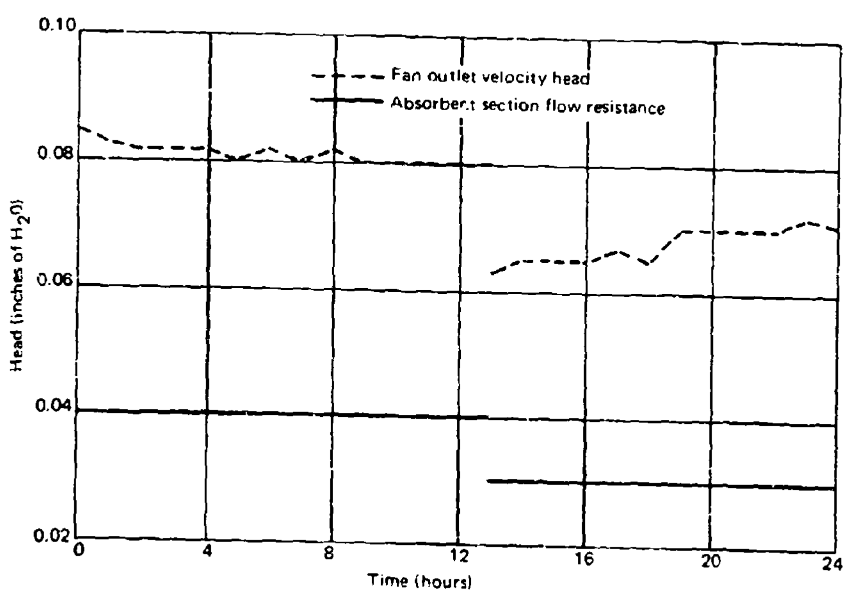


Figure 17. Test results for airflow characteristics.

Table 8. Absorbent Bed Temperature

Test Time (hr)	Absorbent Bed Temperature (°F) for Tray —																							
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
0	69	65	64	65	69	67	69	65	71	66	72	67	66	66	65	64	68	66	69	66	70	66	70	64
0.5	79	73	76	78	80	78	79	77	78	75	76	79	77	74	75	77	79	79	80	79	81	67	75	74
1	85	80	81	85	89	89	85	85	83	82	79	89	85	80	80	85	88	89	86	88	89	67	79	85
1.5	89	87	85	89	91	92	88	90	84	88	81	91	90	87	84	90	90	90	89	90	91	86	83	90
2	90	91	86	93	95	98	90	95	88	93	84	95	95	91	87	95	95	94	90	95	94	91	85	95
2.5	90	94	87	94	94	99	90	96	89	95	85	96	96	94	89	99	95	95	90	96	94	95	87	96
3	92	95	89	95	95	100	91	98	90	97	88	97	96	95	89	108	96	95	92	96	94	96	88	98
4	94	97	91	95	95	102	94	98	92	98	91	96	98	97	91	123	95	94	93	97	94	98	91	98
5	93	96	91	92	93	99	93	96	92	96	92	94	95	96	90	130	94	94	92	94	93	98	91	96
6	95	96	92	95	95	100	95	97	94	97	92	96	97	97	92	96	95	95	95	97	95	98	92	98
7	95	97	93	95	95	100	95	98	94	97	93	96	97	97	92	103	95	95	95	96	95	100	93	99
8	95	97	93	95	96	99	96	97	94	97	93	96	98	97	93	97	96	96	95	96	96	100	93	98
9	96	97	94	97	98	100	97	98	96	97	94	98	98	97	93	98	96	98	97	98	98	100	93	100
10	96	96	96	97	98	100	97	98	95	97	94	98	98	96	94	98	98	98	97	98	98	100	94	93
11	97	95	99	98	99	100	98	98	95	96	91	99	99	95	93	104	98	98	98	98	98	99	93	100
12	98	95	94	98	99	100	93	98	96	97	92	99	99	95	94	130	99	98	98	98	98	99	93	100
13	98	96	95	98	99	100	98	98	96	98	93	99	99	96	95	–	99	98	98	98	98	100	94	100
13[a]	89	87	94	67	90	86	90	85	89	90	92	89	85	88	92	85	89	89	90	88	89	93	92	86
14	93	93	92	94	95	95	94	94	90	94	90	95	94	92	91	94	95	95	94	95	94	96	91	95
15	94	94	94	95	96	96	95	95	92	97	92	96	95	94	93	102	96	96	95	96	95	98	93	96
16	96	98	97	98	98	98	97	98	95	100	95	98	98	98	96	98	98	98	98	98	98	101	95	98
17	98	101	99	99	101	100	99	100	97	103	98	100	99	101	98	100	100	100	99	100	100	104	98	100
18	101	104	101	102	104	102	102	103	99	105	100	104	102	103	101	102	103	102	102	103	102	106	100	102
19	103	105	103	104	105	104	102	104	101	107	101	105	103	105	103	104	104	104	103	104	103	107	101	104
20	104	108	105	104	106	106	104	106	102	109	103	106	104	106	106	126	106	105	104	106	106	109	103	105
21	105	109	106	106	106	108	106	108	103	111	104	108	106	110	106	126	107	107	106	107	106	111	105	106
22	106	111	108	106	108	110	106	109	104	113	105	109	107	111	108	130	108	108	106	109	107	112	105	110
23	106	111	108	106	108	111	106	110	104	113	104	110	108	112	108	134	108	108	106	110	107	113	105	110
24	105	111	107	106	107	110	106	108	104	113	104	108	107	111	108	134	107	108	106	107	106	113	105	106

[a] Restart.

Table 9. Test Chamber Temperature

Test Time (hr)	Temperature (°F) of Thermocouple Located on—							
	Unit Inlet	Unit Outlet	Left Front[a]	Left Center	Left Rear	Right Rear	Right Center	Right Front
0	71	67	73	73	73	71	72	73
0.5	72	70	73	73	73	72	73	73
1	75	78	76	77	76	76	76	76
1.5	78	85	80	79	79	79	79	79
2	80	89	82	82	81	81	82	82
2.5	82	91	84	84	83	82	83	83
3	84	93	86	85	84	83	85	84
4	85	95	87	86	85	85	86	86
5	85	95	87	86	85	85	86	86
6	85	95	87	86	85	85	86	86
7	85	96	88	87	86	86	87	86
8	86	96	88	88	86	86	87	86
9	86	97	88	88	87	86	87	87
10	86	96	89	88	87	87	88	88
11	86	95	88	87	86	86	87	87
12	86	96	88	87	86	86	87	87
13	87	97	89	89	88	88	88	88
13[b]	84	90	85	85	84	84	85	85
14	85	92	86	86	85	85	86	86
15	87	95	88	88	87	87	88	86
16	89	98	90	90	89	89	90	89
17	92	100	93	93	92	93	93	93
18	94	102	96	96	95	95	95	95
19	95	103	97	97	95	97	97	97
20	97	105	98	99	98	99	98	98
21	99	107	100	100	100	100	99	100
22	100	108	100	100	100	100	100	100
23	100	108	100	101	101	101	100	100
24	100	108	100	101	101	101	100	101

[a] Oriented facing fan.

[b] Restart.

The battery and fan motor combination performed well with a total power requirement of only 0.08 hp. Assuming 50% efficiency for the motor and gearbox, the power required at the fan would be only 0.04 hp, which is acceptable. It should also be noted that the unit flow resistance did not increase with absorbent use as had been anticipated (Figure 17). Absorbent activity as shown by the thermocouple records in Table 8 was relatively constant. The thermocouple placement is shown in Figure 18. This would indicate a good match of bed airflow resistance and airflow pattern through the unit.

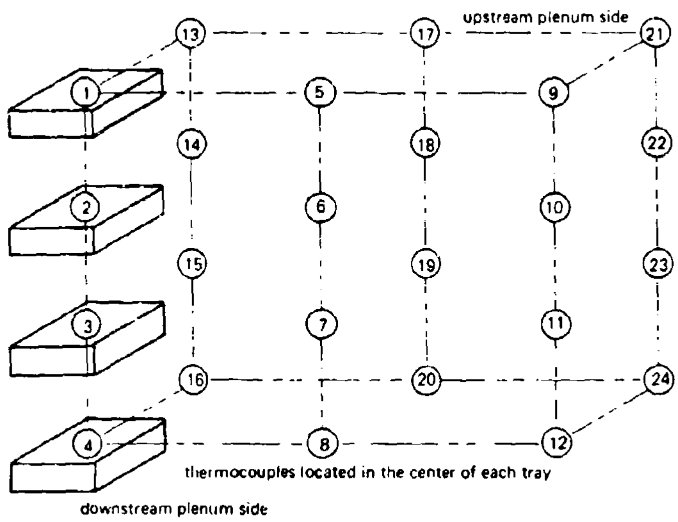


Figure 18. Thermocouple placement.

DISCUSSION OF RESULTS

In general, the chemical performance of the unit was excellent. No flaws were noted in the absorbent section. That is, the absorbent trays performed effectively because each was properly shaped and located within the unit for equal influent air distribution and flow rate.

Minor structural problems were encountered which could be corrected by simple design modification. For example, using latches to seal the plenum doors would eliminate the problem caused by structural deformation. In addition, the air distribution baffles or panels should be moved from the absorbent section to the plenum doors in order to simplify tray loading.

Electrical and mechanical problems were more significant. The battery charger must be isolated from the emergency electrical system to avoid battery discharging when 110-VAC power is not available, and when it is desired to operate the fan motor from a 110-VAC supply. A proposed scheme is shown in Figure 19. The gearbox must be replaced and preferably eliminated. It is recommended that the No. 166A100-7 Globe Motor be replaced by a No. 166A100-10 Globe Motor, or equal unit, which has half the speed. This motor combined with a 4:1 belt pulley speed reduction system and 24-VDC power supply should provide the proper fan speed without the

gearbox. The safety pressure switch in the oxygen line should be replaced by one with a lower pressure actuation limit. Although the orifice or some restriction should be retained in the oxygen line downstream to the pressure regulator in order to activate the pressure switch, flow should be metered by a flowmeter rather than by the orifice. In addition, the flowmeter should be calibrated directly in terms of the number of people on board. Using a chart or formula to convert need to flowrater setting would be cumbersome and quite probably ineffectual. Steps should be taken (for example, painting directional arrows on the trays) to insure that the trays are properly oriented when they are inserted into the unit so that the cam lugs will slide on their guide rails. Finally, the battery charger should be shielded as much as possible from dampness in the shelter during emergency use. Placing the charger in a well-ventilated sheet metal enclosure would allow condensation to occur outside of the charger thereby minimizing potential shorting problems.

Although problem areas were encountered, the solutions seem straightforward, and it was concluded that the test results were affirmative.

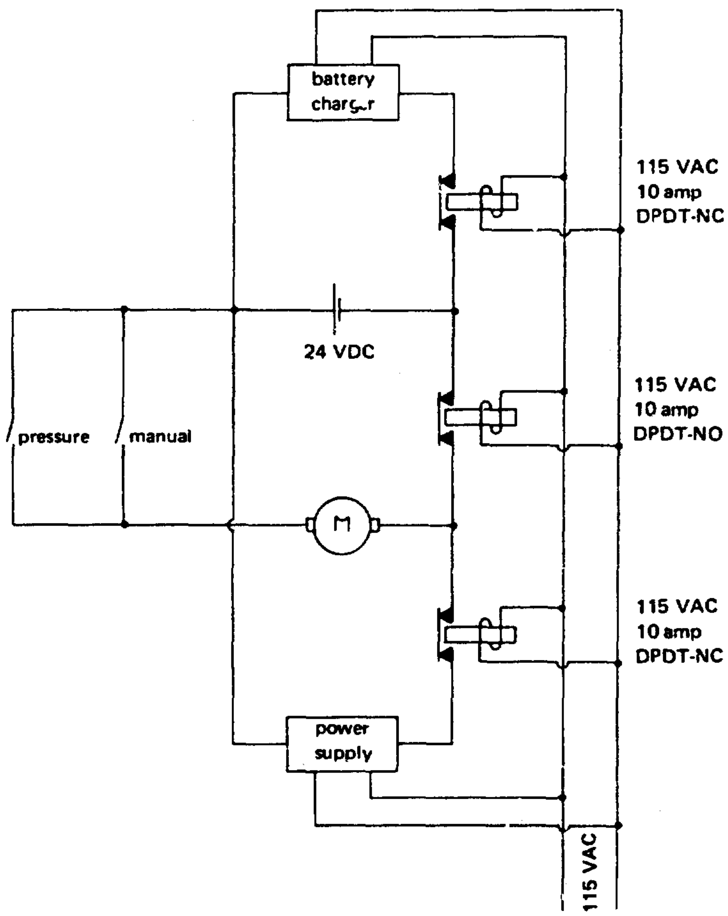


Figure 19. Battery charger isolation schematic.

OPERATING INSTRUCTIONS

Adequate instructions are essential. Instructions should be extremely simple and terse because most people will simply not bother to read a detailed instruction manual. All possible judgements should be eliminated. The reason why the unit is required and a simple explanation of how and why it works should be provided because a promulgation of misinformation must be avoided. These requirements are quite obviously not compatible. A variety of people will be involved. Some will be content to follow instructions, others will not; skepticism, curiosity, inadequate or erroneous prior information are all possibilities. A possible solution is to prepare both a very brief instruction list and also a synopsized instruction manual with a detailed and descriptive appendix. It is recommended that this problem be studied in depth.

The occupants of the shelter must be made aware that a dangerous environmental situation exists in a sealed habitat. The existance of the unit and its intended function must be conspicuous. In addition, the unit should be activated when the shelter is sealed because there is no confidence in the ability of untrained people to use emergency oxygen and carbon dioxide detectors successfully.[25] Even worse is to base the need for air revitalization on opinion.[8] The decision to seal the shelter might well be premature; this does not, however, affect the internal environment.

It would be preferable if Baralyme could be prepackaged and stored within the unit ready for use. This is not possible at the present time. The occupants of the shelter must load the unit. This will consist of emptying the contents of one 5-gallon tin (40 pounds of absorbent) into each of the 24 trays. All of the Baralyme trays must be filled evenly. The airflow through the absorbent section of the unit will take the path of least resistance. If some of the trays are not filled evenly, or even worse if left empty, the airflow will simply bypass the absorbent and render it ineffectual.

Another problem could involve preparing the unit for use, loading the trays, activating the fan manually, but neglecting to turn on the oxygen supply. The unit will control the carbon dioxide level well below any sensory warning threshold. The lack of oxygen is insidious in that it is not accompanied by disturbing sensory phenomena in the absence of an increased carbon dioxide concentration. In short, no one will miss the oxygen.

It is assumed that the following instruction sheet will be made conspicuous and placed near the entrance to the shelter or some other center of activity as well as by the unit itself.

1. Locate the air revitalization unit.

2. When the shelter is sealed, proceed to operate the unit. If the shelter is not sealed, the unit will not be required.

3. Unlatch drawbars A around doors B and C. Figure 20.
4. Open doors B and C and remove trays D.
5. Fill each tray with the contents of one 5-gallon tin of Baralyme.
6. Spread the Baralyme evenly in each tray.
7. Replace all trays. Make sure that each tray is filled evenly.
8. Close doors B and C and latch tight with drawbars A.
9. Switch on fan E. NOTE: Make certain fan is operating before proceeding.
10. Open cylinder valves F.
11. Open stop valve G.
12. Set pressure regulator H to give desired flow through flowmeter I. NOTE. Screw regulator handle in to increase flow.

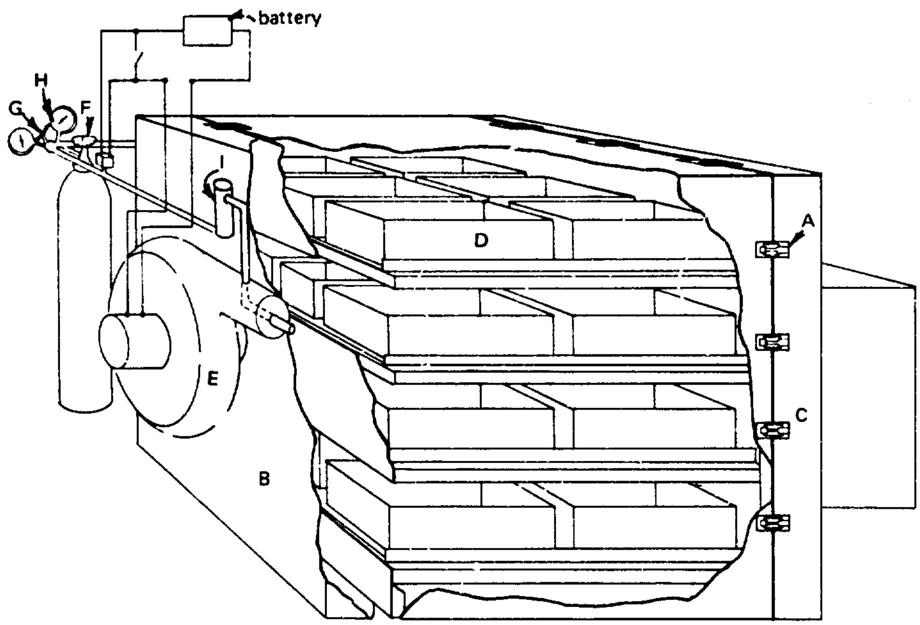


Figure 20. Diagram for operating instructions.

CONCLUSIONS

1. Dry chemical carbon dioxide absorbents are superior to both chemical solution absorbents and regenerative absorption systems for short-term, limited power application.

2. Proper absorbent bed configuration and influent gasflow rates are essential for both absorbent effectiveness and minimal circulation power requirements. The optimum bed thickness was found to be 5 inches, with a superficial velocity of 7.5 fpm.

3. If power input is to be conserved, careful component selection is mandatory since efficiency was found to drop sharply with power requirement.

4. For survival shelter applications, Baralyme was selected as the most promising dry chemical carbon dioxide absorbent that is available commercially.

5. Pressure cylinders, when used with a flowmeter, were selected as the most promising means for oxygen storage and dispersal.

6. An activated charcoal filter was selected as the most promising means for odor control. Trace gas control was not attempted.

7. Either battery or a manual power supply system is suitable. There is little to choose between the two systems. The manual system, which [illegible] a bicycle-driven fan arrangement, is less expensive and is easier to store. The battery system, on the other hand, is easier to operate and, in that sense, is safer.

8. In general, the chemical, mechanical, and structural aspects of the design of the air revitalization unit have been resolved. A similar assessment cannot be made for the human element inherently involved with the operation of the unit.

RECOMMENDATIONS

1. Existing emergency lighting systems should be investigated because it is probable that only slight modifications would be required in order to accommodate the power requirement of the air revitalization unit. An integrated system would probably involve extra batteries which would share a common charger.

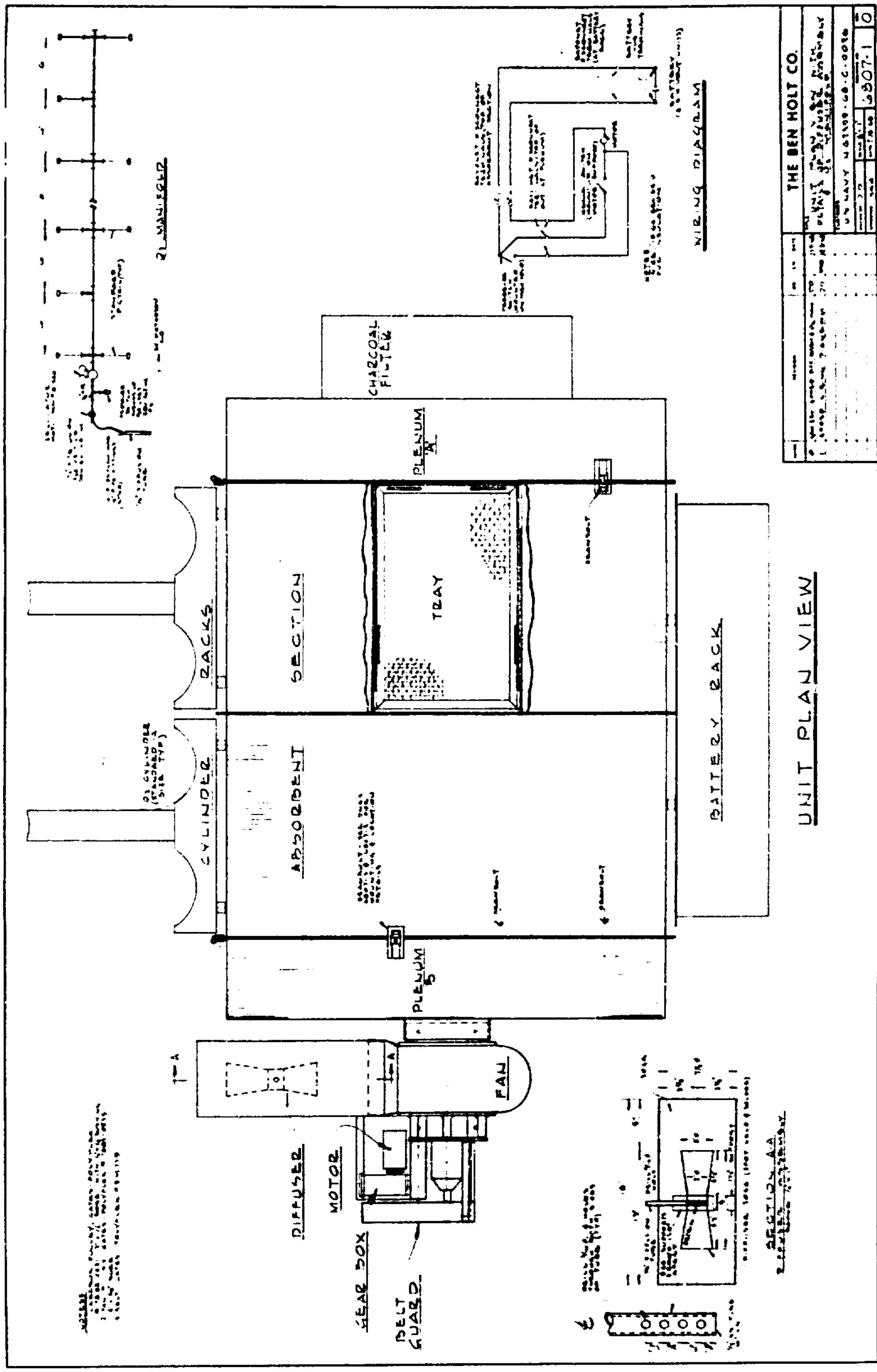
2. Research is needed to determine the normal power capabilities of a realistic cross section of male subjects exposed to elevated temperatures and vitiated atmospheres.

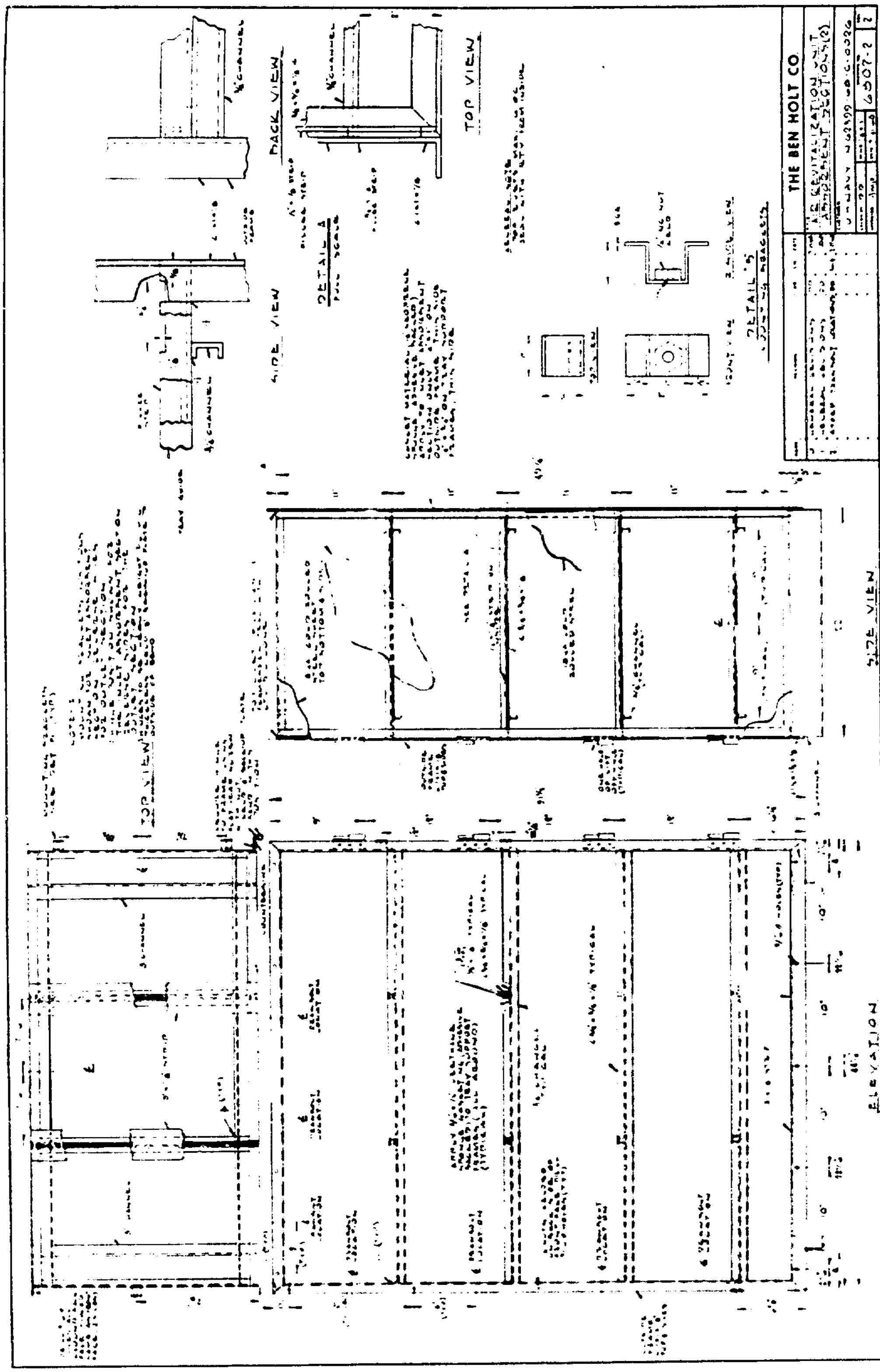
3. Research is recommended to determine levels of competence of untrained people under stress. The ability to follow instructions and to use life-support equipment properly is of primary concern.

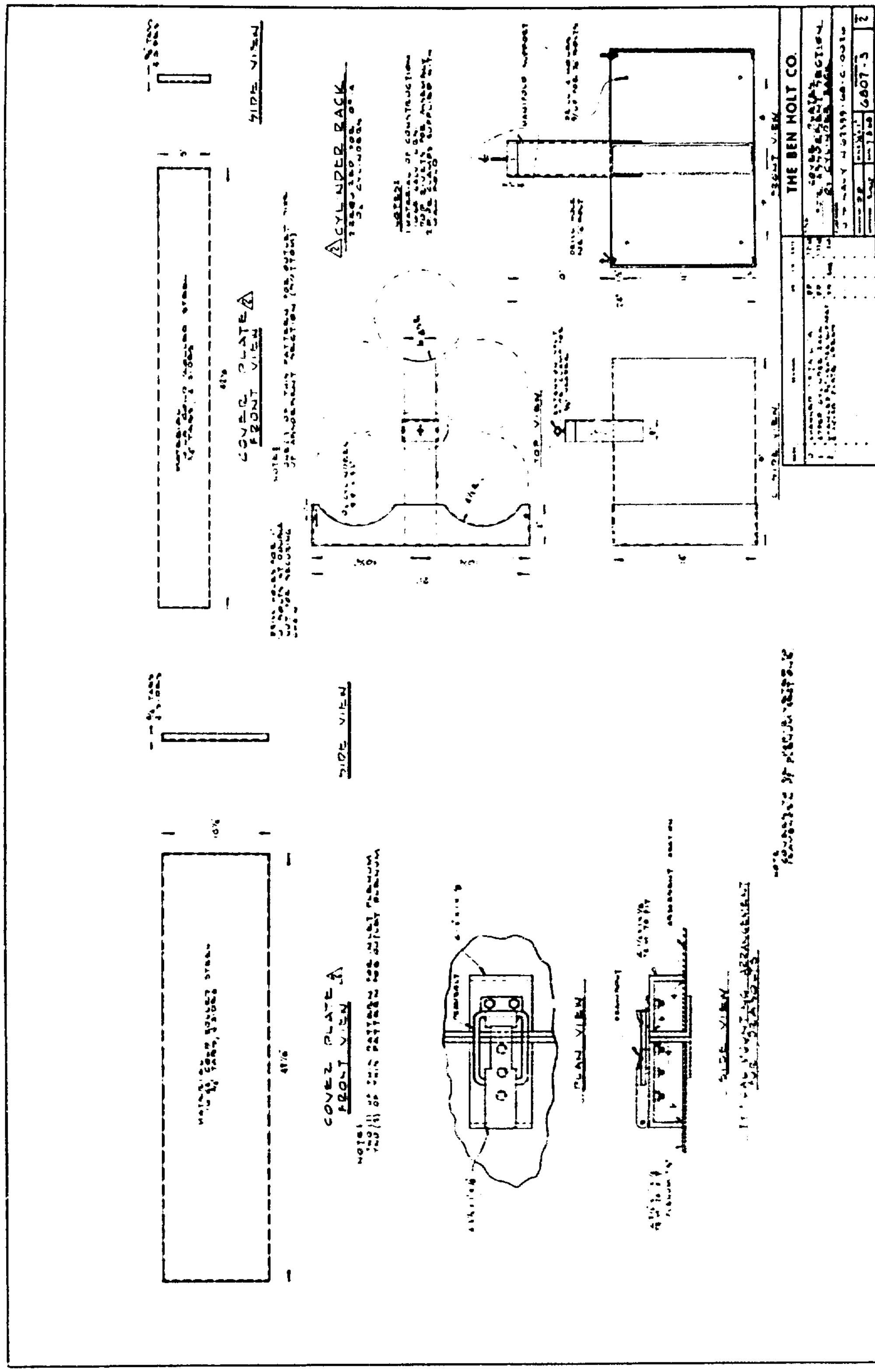
4. Continued research is required to improve nonregenerative carbon dioxide absorbents chemically and to improve mechanical aspects of absorption techniques.

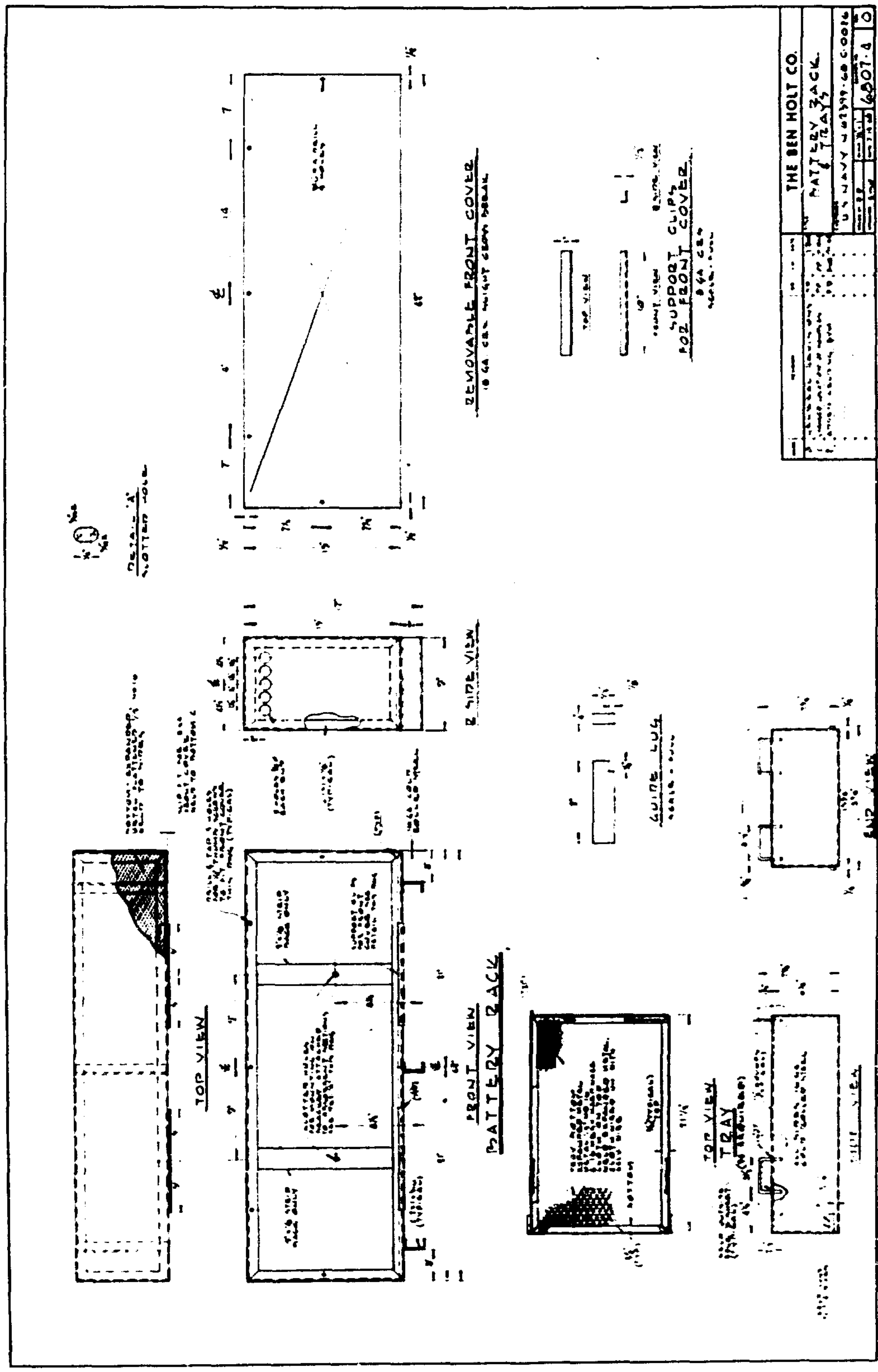
Appendix

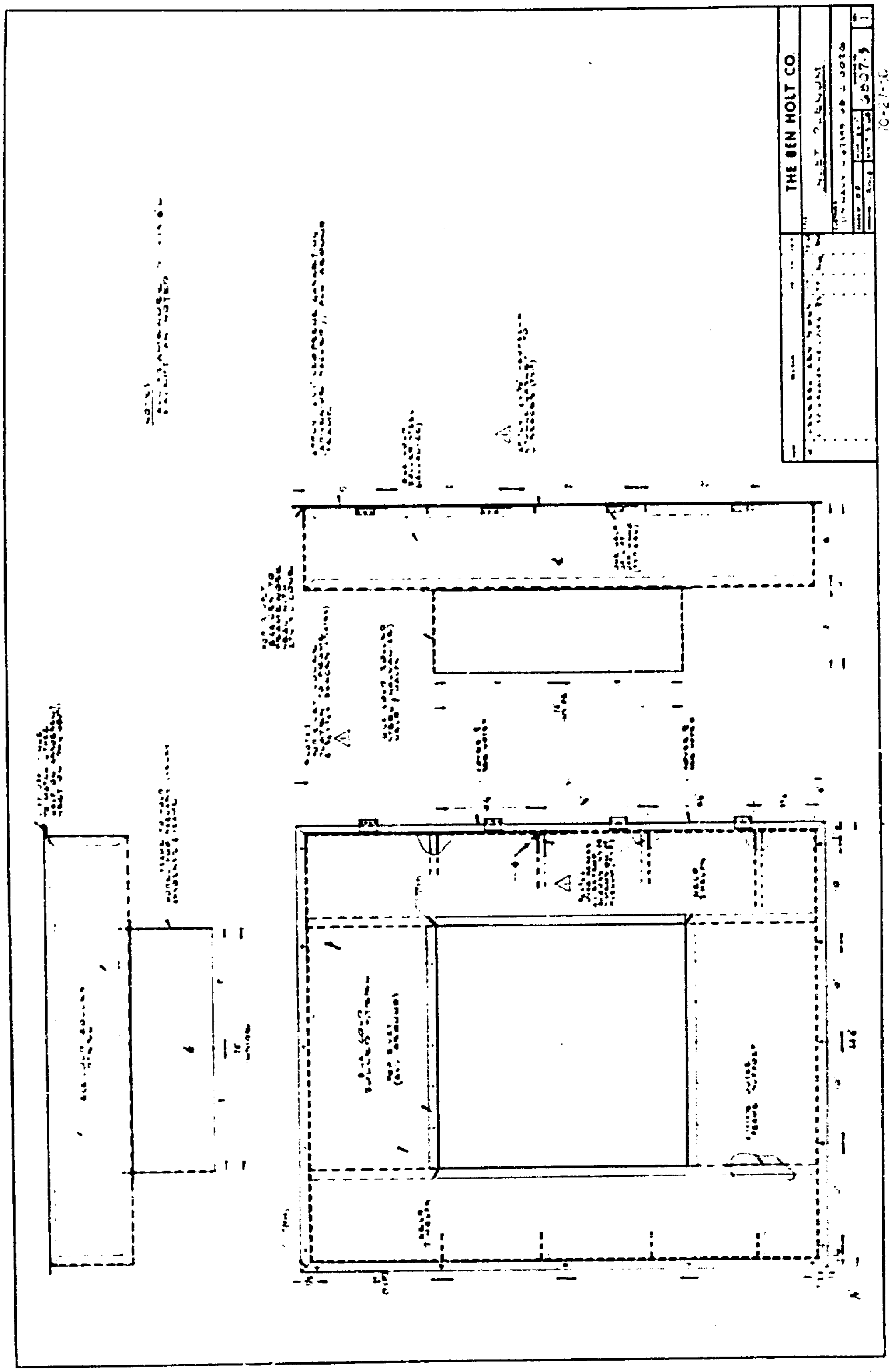
AIR REVITALIZATION UNIT DRAWINGS


UNIT PLAN VIEW
BATTERY RACK
CYLINDER RACKS
ABSORBENT SECTION
TRAY
PLENUM A
PLENUM B
CHARCOAL FILTER
FAN
DIFFUSER
MOTOR
GEAR BOX
BELT GUARD
WIRING DIAGRAM
SECTION AA
THE BEN HOLT CO.
6807-1


THE BEN HOLT CO
ELEVATION
SIDE VIEW
TOP VIEW
BACK VIEW
SIDE VIEW
TOP VIEW
6507-2


THE BEN HOLT CO.
CYLINDER RACK
COVER PLATE
FRONT VIEW
SIDE VIEW
TOP VIEW
PLAN VIEW
6807-3


THE BEN HOLT CO.
BATTERY RACK & TRAYS
TOP VIEW
FRONT VIEW
BATTERY RACK
REMOVABLE FRONT COVER
SUPPORT CLIPS FOR FRONT COVER
GUIDE LUG
TOP VIEW
TRAY
END VIEW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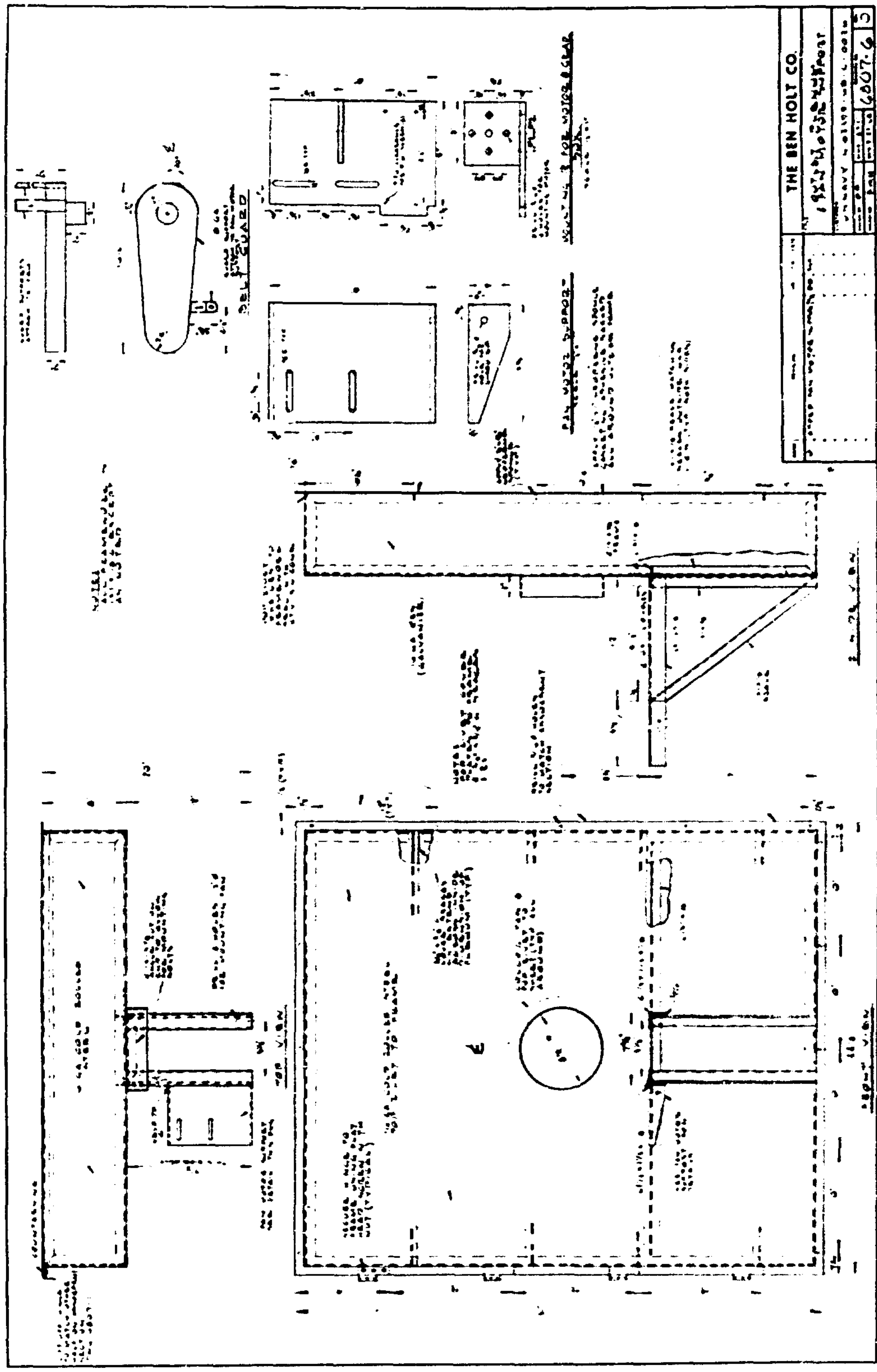
THE BEN HOLT CO.

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13. ABSTRACT

An air revitalization unit for use with sealed survival shelters without an external power supply was developed. The unit is capable of supplying oxygen to and removing carbon dioxide and odors from a 100-man personnel shelter for a 24-hour period. The system utilizes (1) a dry chemical absorbent (Baralyme) for carbon dioxide removal, (2) pressure cylinders for the oxygen supply, (3) an activated charcoal filter to remove odors, and (4) a battery-powered fan for air circulation. A prototype unit was designed, fabricated, and tested. Following tests of individual components, a 24-hour continuous test of the unit was completed. In general, the test results for the chemical, mechanical, and structural aspects of the air revitalization unit were affirmative. A similar assessment cannot be made for the human element inherently involved with the operation of the unit.

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